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E ℓC51843 Carnegie-Illinois Steel Corp.
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A STUDY OF BALLISTIC AND METALLURGICAL CHARACTERISTICS OF STEEL AIRCRAFT ARMOR, by J. M. Hodge and H. V. Joyce. June 25, 1948, 58p. illus. diagrs.

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I. Hodge, J. M.
II. Joyce, H. V.

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(1)

6 A Study of Ballistic and Metallurgical Characteristics of Steel Aircraft Armor,

10 J. M. Hodge and H. V. Joyce
[redacted]

For

The Naval Research Laboratory
Anacostia Station
Washington 20, D. C.

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Abstract

This report is a comprehensive review of the metallurgical factors pertinent to the production and testing of steel aircraft armor plate.

The development of aircraft armor is summarized and the relative importance of types of steel aircraft armor plate is outlined.

It is shown that the degree to which homogeneous steel aircraft armor resists penetration of armor piercing projectiles is dependent upon the toughness of the plate material when heat treated to an optimum hardness for the given ballistic condition. The optimum microstructure for toughness is tempered martensite. Inhomogeneities in the plate material lower the toughness. Suitable compositions for homogeneous armor are those which will quench out to full martensite on the quenching treatment used and will permit use of tempering temperatures high enough to avoid temper embrittlement.

References to a number of World War II investigations are used to show that face hardened steel armor resists penetration by breaking up the projectile and the plate's ability to break up a projectile is dependent upon a high face hardness. It is suggested that there is an optimum face hardness. It is also shown that there is an optimum depth of hardening and an optimum back hardness for a given test condition. Carburized armor, Pluramelt armor and as yet undeveloped composite armors are discussed briefly.

Finally it is shown that war time improvements in quality are reflected by higher specification requirements. The possibilities of further improvement in homogeneous armor appear to be limited, while it seems reasonable to expect additional improvements in face hardened armor.

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Preface

In November 1946, the Carnegie-Illinois Steel Corporation undertook a contract with the Naval Research Laboratory, Anacostia Station, Washington, D. C. to conduct a study of steel aircraft armor improvement during the World War II period. The specifications for the study set forth by the Naval Research Laboratory were as follows:

1. Summarize results of tests of experimental steel aircraft armor with caliber .50 A. P., 20mm A. P. and 20mm H. E. at Dahlgren, Va. pointing out in the case of each group of tests what variables were under investigation.

2. After conferring with Army representatives as to experimental steel aircraft armor tests make a summary of what appear to be the most significant Army results.

3. Discuss the results of these tests. Give particular attention to variables for which ballistic test results showed great sensitivity.

4. As completely as this survey and its incidental studies permit, list the investigation which might be expected to provide basic information necessary for additional steel armor improvement.

5. Prepare a report embodying (1), (2), (3) and (4) for submission to the Naval Research Laboratory.

The authors' proposed method of study was submitted to the Naval Research Laboratory in outline form in February 1947. Since then, the authors or their associates have visited the Navy Department Bureau of Ordnance and Bureau of Aeronautics, the Naval Proving Ground, the War Department Office of Chief of Ordnance, the Watertown Arsenal and the Naval Research Laboratory in search of data and reports to be included in the survey. Naturally, as in any work of this type, the authors must admit misgivings concerning the

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percentage of data which may have escaped review by their methods. Nevertheless, it is believed that all important phases of the metallurgical design of steel aircraft armor have been studied during the course of the survey and the findings reported herein are generally supported by published references. The exceptions are a few instances where the authors have had to call upon their own experiences and knowledge of related products to establish a hypothesis or to analyze non-integrated data.

The authors wish to express their appreciation for the cooperative attitude shown by representatives of all of the afore mentioned agencies. Their advice and aid in selecting reports for study and their help in making material available greatly facilitated the authors' work.

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HVJ/pb
June 25, 1948

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PART 1

INTRODUCTION

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INTRODUCTION

I. Use of Armor in Aircraft

While references to the use of armor plate in aircraft may be found in the literature as far back as 1916, aircraft armor as it is known today is, generally speaking, a development of the World War II period. Prior to World War II, armor plate installed in airplanes was termed "thin armor", "light armor" or "bullet proof steel" and was the same armor as that used on light tanks and armored cars. Even as late as 1941 the services did not have a specification for aircraft armor. In that year, however, joint industry and service committees were formed to develop higher quality armor and to establish specifications for procurement of the same.

The aircraft armor problem was not a simple one primarily because of the limitation of weight. Perhaps in no other application of armor is the object of getting the greatest protection from the least weight of more importance than in the design and fabrication of aircraft armor. Pursuit planes being built in 1941 carried but 200 pounds of armor plate and the latest model of the "Flying Fortress" (the B17-E) had less than 2000 pounds of armor.

Had there been but one type of attack against which protection was required, the problem would have been somewhat simplified. Needless to say, however, such was not the case. As well as anti aircraft fire from the ground, head on, beam and rear attacks by enemy fighters against bombing planes were to be expected. Furthermore, enemy airplanes were known to carry several caliber of guns loaded with several types of ammunition. It was also reasonable to assume that new types of armament and ammunition, of which our services were not aware, could be encountered on any mission.

The design and installation of the armor itself also tended to complicate the problem. Since obviously the whole airplane or even the whole fuselage could not be armor plated, the limited amount of armor to be carried was distributed mostly within the cabin in a manner to afford protection to each crew member's station. An attacking missile therefore in many cases had to pass through the fuselage skin and various structural members before impacting the armor plate. It was discovered in early tests that as a projectile defeats primary obstacles such as the Duralumin skin and internal braces, it is likely to be tumbled and its impact against the armor plate is unlikely to be nose-on. A considerable amount of experimental work during 1941 was based on this fact. Various materials of varying thicknesses were set up at varying distances from armor plate in attempts to find an optimum combination and arrangement of materials. It was eventually determined, however, that the value of tipping screens or yaw plates is doubtful since the fuselage itself and interior parts in line of flight of a projectile impart sufficient yaw or tumbling action.(1)

It may be readily seen, therefore, that at least five different types of attack had to be considered in the design and installation of armor in aircraft. The five attacks may be summarized as follows:

1. Impact by armor piercing projectiles striking the armor plate at normal (perpendicular to the surface of the plate).

2. Impact by armor piercing projectiles striking the armor at oblique angles.

3. Impact by high explosive projectiles.

4. Impact by projectiles yawed or tumbled by prior impact on the airframe skin or structural member.

5. Impact by fragments from exploded shells.

---

(1) Numbers in parenthesis pertain to references appended to this report.

II. Types of Armor Plate Used in Aircraft

In a survey of the literature preparatory to an investigation of light armor, the Naval Research Laboratory in 1935 reviewed work reported in Japan by Honda in 1930 and 1933.(2) Honda had reported that of seven non-ferrous materials investigated, the aluminum alloy, Duralumin, on the basis of weight for weight, offered greatest resistance to perforation by standard (.25 caliber) Japanese ammunition. Tests conducted at Watertown Arsenal, Aberdeen Proving Ground and the Naval Research Laboratory in the period of 1934 to 1941 showed that under various conditions Duralumin exhibited resistance characteristics comparable with those of steel. In the work performed at the Naval Research Laboratory, Dowmetal was also used in comparison tests. Simultaneously there were conducted many tests of face hardened and rolled homogeneous steel armor of thicknesses feasible for use in aircraft, but, generally, the results were of interest only insofar as they served to answer some immediate problem. Laminated plastics were also tested and found to have merit under certain limited conditions.

In February 1943, the Watertown Arsenal Laboratory was authorized to prepare a substantially informative report to give data usable in armor design. In this task an attempt was made to collate, integrate and analyze available data on the characteristics of the various armor plate materials. The report, prepared by J. F. Sullivan, was published early in 1944.(3)

After a review of the data available, Sullivan narrowed his study to face hardened steel, rolled homogeneous steel (340-380 BHN), Duralumin and Dowmetal. In his final report, Sullivan reviewed how factors affecting the manner of failure of armor explain the alternative superiority of different materials under different conditions of attack. It was pointed out that where the lower density of a material allows its use in thicker sections without additional weight, dimensional conditions arise favoring the ability of such material to resist perforation. Thus Duralumin which is only 0.36 times as dense as steel may overmatch an attacking projectile while an equivalent weight of steel may be overmatched by the same projectile. Under such conditions, it is possible that the steel will require less projectile energy to bring about failure. Figure 1 (copied from Sullivan's report) illustrates: (1) how a difference in thickness of different materials of equal weight results from their variant densities, (2) the necessity of using a greater area of armor obliquely emplaced to protect a fixed area normal to the line of fire and (3) how a variation in the ratio of plate thickness to projectile core diameter tends to influence the manner in which plate failure will occur.

Sullivan's observations regarding the relative merits of the different materials studied are quoted verbatim below. The reader is reminded that the report from which the conclusions are quoted was prepared in late 1943. In view of the fact that improvement of aircraft armor continued after this date, it is possible that some of the observations may no longer hold true.

1. "Under no contemplated conditions will the use of rolled homogeneous steel or Dowmetal assure the maximum resistance (to perforation by small arms projectiles) per unit weight employed."

a. "In general, when the obliquity of emplacement with respect to the anticipated line of fire is greater than 52°, or when the ratio of plate thickness (weighed) to projectile core diameter is less than 0.6, the use of 24ST Duralumin will assure maximum resistance (to perforation by small arms projectiles) per unit weight employed."

b. "Under all other conditions, the use of face hardened steel armor will assure maximum resistance to perforation." (See Figure 2)

2. "Under some conditions, the resistance (to shock) of rolled homogeneous steel armor is superior to that of face hardened steel."

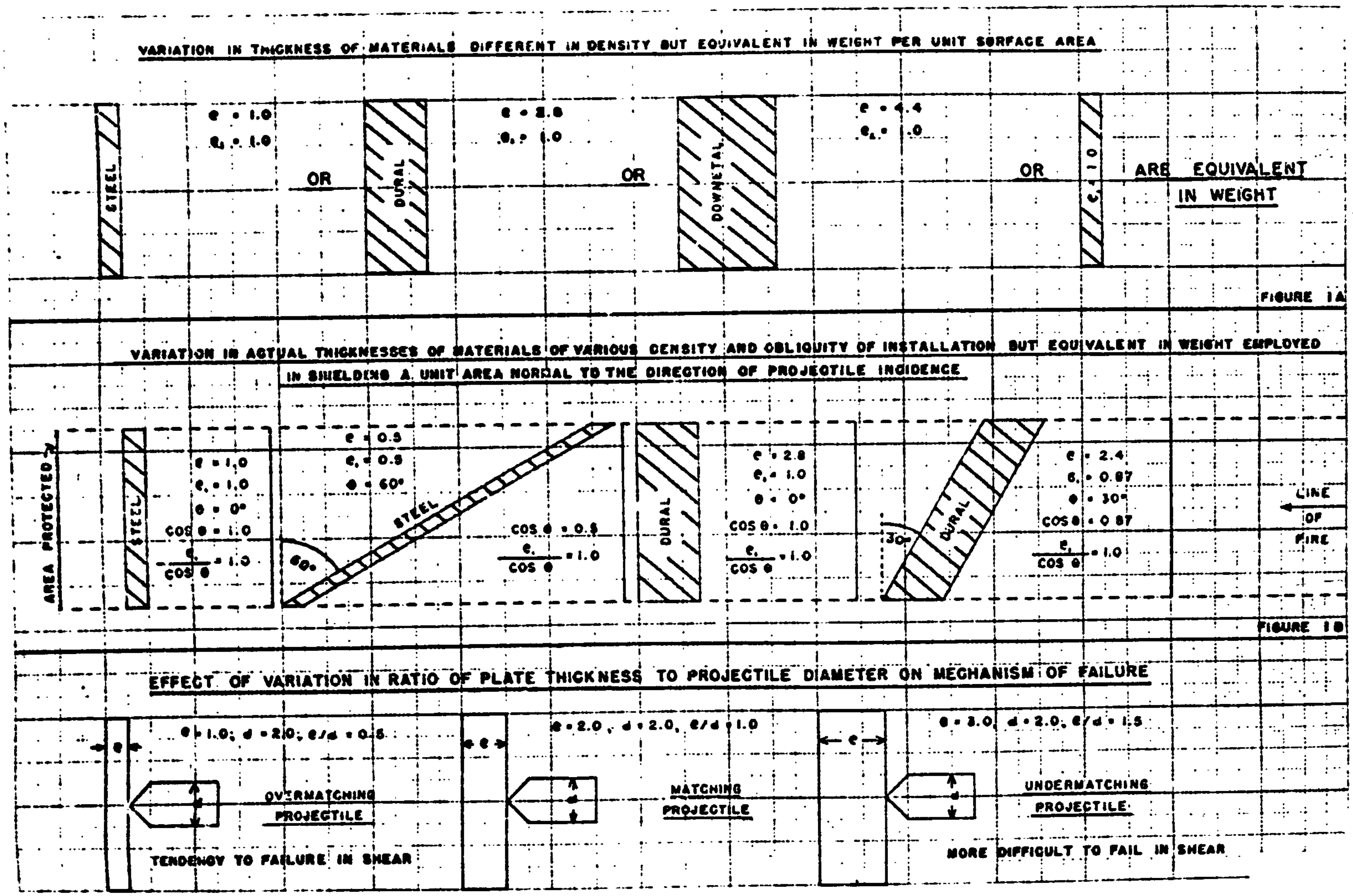
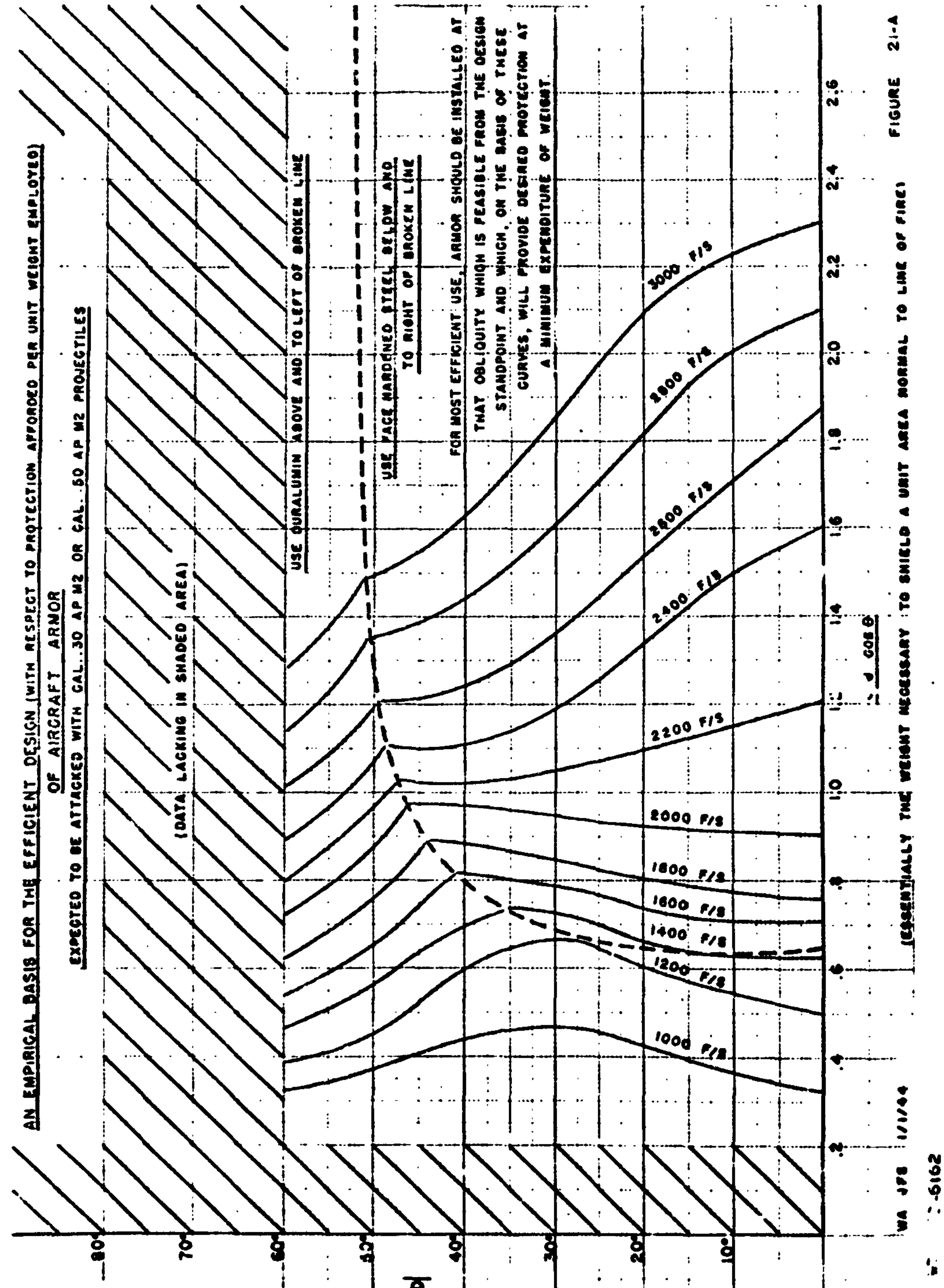

VARIATION IN THICKNESS OF MATERIALS DIFFERENT IN DENSITY BUT EQUIVALENT IN WEIGHT PER UNIT SURFACE AREA
STEEL
e = 1.0
e₁ = 1.0
OR
DURAL
e = 2.8
e₁ = 1.0
OR
DOWMETAL
e = 4.4
e₁ = 1.0
OR
e₁ = 1.0
ARE EQUIVALENT IN WEIGHT
FIGURE 1A
VARIATION IN ACTUAL THICKNESSES OF MATERIALS OF VARIOUS DENSITY AND OBLIQUITY OF INSTALLATION BUT EQUIVALENT IN WEIGHT EMPLOYED IN SHIELDING A UNIT AREA NORMAL TO THE DIRECTION OF PROJECTILE INCIDENCE
AREA PROTECTED
STEEL
e = 1.0
e₁ = 1.0
θ = 0°
COS θ = 1.0
e₁ / COS θ = 1.0
e = 0.5
e₁ = 0.5
θ = 60°
STEEL
60°
COS θ = 0.5
e₁ / COS θ = 1.0
DURAL
e = 2.8
e₁ = 1.0
θ = 0°
COS θ = 1.0
e₁ / COS θ = 1.0
30°
DURAL
e = 2.4
e₁ = 0.87
θ = 30°
COS θ = 0.87
e₁ / COS θ = 1.0
LINE OF FIRE
FIGURE 1B
EFFECT OF VARIATION IN RATIO OF PLATE THICKNESS TO PROJECTILE DIAMETER ON MECHANISM OF FAILURE
e = 1.0; d = 2.0; e/d = 0.5
OVERMATCHING PROJECTILE
TENDENCY TO FAILURE IN SHEAR
e = 2.0, d = 2.0, e/d = 1.0
MATCHING PROJECTILE
e = 3.0, d = 2.0, e/d = 1.5
UNDERMATCHING PROJECTILE
MORE DIFFICULT TO FAIL IN SHEAR

FIGURE I


AN EMPIRICAL BASIS FOR THE EFFICIENT DESIGN (WITH RESPECT TO PROTECTION AFFORDED PER UNIT WEIGHT EMPLOYED)
OF AIRCRAFT ARMOR
EXPECTED TO BE ATTACKED WITH CAL .30 AP M2 OR CAL .50 AP M2 PROJECTILES
(DATA LACKING IN SHADED AREA)
USE DURALUMIN ABOVE AND TO LEFT OF BROKEN LINE
USE FACE HARDENED STEEL BELOW AND TO RIGHT OF BROKEN LINE
FOR MOST EFFICIENT USE, ARMOR SHOULD BE INSTALLED AT THAT OBLIQUITY WHICH IS FEASIBLE FROM THE DESIGN STANDPOINT AND WHICH, ON THE BASIS OF THESE CURVES, WILL PROVIDE DESIRED PROTECTION AT A MINIMUM EXPENDITURE OF WEIGHT.
3000 F/S
2800 F/S
2600 F/S
2400 F/S
2200 F/S
2000 F/S
1800 F/S
1600 F/S
1400 F/S
1200 F/S
1000 F/S
.2
.4
.6
.8
1.0
1.4
1.6
1.8
2.0
2.2
2.4
2.6
(ESSENTIALLY THE WEIGHT NECESSARY TO SHIELD A UNIT AREA NORMAL TO LINE OF FIRE)
10°
20°
30°
40°
50°
60°
70°
80°
θ
(OBLIQUITY OF INSTALLATION WITH RESPECT TO LINE OF ATTACK)
FIGURE 21-A
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-5162

FIGURE 2

3. "Except in the case of attack by direct impact of high explosive projectiles, the shock resistance of 24ST Duralumin is equivalent to or better than that of steel."

4. "Coincident with failure by perforation of armor piercing projectiles, 24ST Duralumin exhibits a tendency toward spalling."

5. "Low temperature enhances the resistance to perforation of 24ST Duralumin, rolled homogeneous steel and face hardened steel."

6. "Although low temperatures may affect deleteriously the shock resistance of steel, they apparently do not lower the shock resistance of Duralumin."

7. "Inasmuch as it is considered that resistance to perforation is of prime importance in any consideration of aircraft armor, design may well be based on observation 1."

8. "The most strategic placement of armor will vary from time to time with tactics of the opponents and contemporary design may best be decided on the basis of study of the very latest intelligence reports from the theaters of operations."

9. "Under attack of projectiles of larger caliber, or different design or quality, the region of superiority of 24ST Duralumin over face hardened steel may be expected to be extended."

It is apparent by now that the term "aircraft armor" is a generic one covering different types of steel armor plate as well as different types of non-ferrous armor plate. A review of the non-ferrous types is not within the scope of this study, it being understood that a similar study of these types of armor plate is currently being made by the Naval Research Laboratory.

At this point it may be well to mention why some special kinds of the two main types of steel armor receive no further mention in the report. Non-magnetic steel armor, which falls under the homogeneous type , was found to afford so much lower resistance than magnetic steel armor that a review of its ballistic characteristics has been considered to be of little value. Furthermore, much of the demand for non-magnetic armor, once necessary, passed with more effective shielding of aircraft instruments. Likewise, although much work was done in attempts to develop a laminated or "sandwich" kind of face hardened armor, in general on a basis of weight for weight, the ballistic qualities of such armor were inferior to those of solid face hardened steel armor.

III. The Manufacture of Steel Armor

While certain cast steel armor sections are used on tanks, the relatively lighter gauges of aircraft armor precludes the use of castings for this application. As far as is known, all steel aircraft armor was and still is processed by rolling. Details of the manufacturing processes of course vary from company to company depending more or less on the facilities available. Both open hearth and electric furnace melting practices have been used with success.

Little information regarding steel making and rolling practices is found in published reports. Certain logical assumptions can be made however. Because clean steel is imperative, melting practices must be held under rigid control from selection of the scrap charge to tapping. Ingot mold design is also an important factor affecting soundness of the finished armor plate. Since the ability of steel armor to resist shock depends to some extent on the absence of directional properties, the manner in which a plate is rolled takes on added importance.

Cleanliness, soundness and lack of directional properties are prerequisites for high quality steel aircraft armor. The same characteristics may also be prerequisites for other products which still would not be interchangeable with armor. The distinctive features of armor plate are imparted to the steel by heat treating the rolled plates. Starting some time before World War II, the heat treatment of steels began to assume a more scientific aspect. The accumulated knowledge of physical metallurgy was naturally applied to the production of steel aircraft armor during the war years. The experiments with refrigeration treatments to accomplish complete transformation of the face on face hardened armor serves to illustrate the degree to which metallurgical science was used. The use of the metallurgical microscope, micro-hardness testing equipment, impact test machines and other laboratory tools to test and investigate the results of heat treatment attests to the control exercised over the treating processes.

It is in order to mention that the intense application of metallurgical science to the production of aircraft armor came about through complete cooperation between the producers and various government agencies. The Armor and Projectile Laboratory and Light Armor Battery at the Naval Proving Ground, Dahlgren Va., the Watertown Arsenal Laboratory and the Armor Branch of the Ordnance Research Center at the Aberdeen Proving Ground all contributed greatly to the improvement of aircraft armor. Valuable assistance was also had from such laboratories as the Battelle Memorial Institute through projects conducted by the War Metallurgy Committee of the National Defense Research Council.

Much of the interest of the last named agency above was directed toward development of low alloy steel armor in an effort to conserve strategic materials. While the results of such projects were not too fruitful where steel aircraft armor was concerned, considerable knowledge concerning hardenability, heat treating and welding of steel armor in general was made available to armor producers through the projects.

PART 2

HOMOGENEOUS ARMOR

HOMOGENEOUS ARMOR

Fundamentals

I. The Effect of Hardness

The resistance of homogeneous armor to penetration by a projectile, depends, of course, upon the plate's ability to absorb the kinetic energy of the projectile. This energy is absorbed almost entirely by plastic flow of the plate material, and homogeneous armor, therefore, differs from face hardened armor in that it is designed primarily to permit a maximum energy absorption from plastic flow of the plate material without necessarily any deformation of the projectile, while the resistance of face hardened armor is dependent primarily upon its ability to deform or break the projectile and the absorption of energy by plastic flow is a secondary consideration.

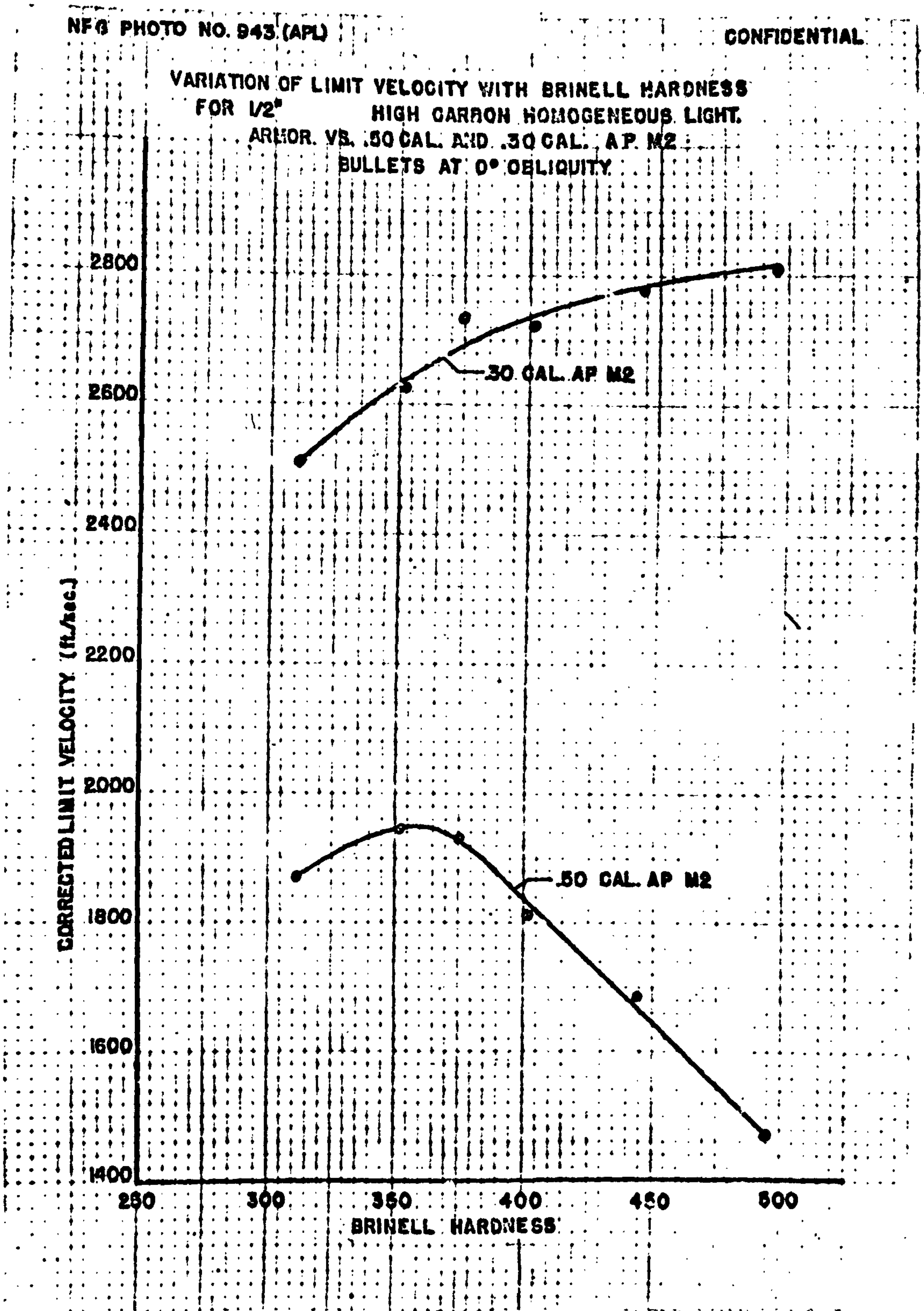
This energy absorption by plastic flow is a function of both the hardness and ductility of the homogeneous armor material. It must have a relatively high hardness, in order that the plastic flow may occur at a high energy level, and it must have a high ductility in order that plastic flow may continue to large strains prior to fracture. This combination of high hardness and high ductility is commonly referred to as toughness and this attribute is the prime requisite for successful homogeneous armor. All of the metallurgical factors to be discussed in this part of the report and the research and development work to be described and proposed are, therefore, primarily aimed at the attainment of armor with optimum properties in respect to toughness.

Toughness, however, as described above, involves a combination of hardness and ductility and these two properties are not entirely compatible, as in general, the ductility tends to decrease as the hardness increases. Furthermore, the plastic flow behavior and therefore the ductility is markedly affected by external conditions such as the direction and magnitude of the applied stresses, the rate of application of these stresses and the temperature. Thus, in order to maintain an adequate ductility to insure high energy absorption by plastic flow, it may frequently be necessary to restrict the hardness range to a value consistent with the particular set of external conditions which are imposed.

This is illustrated by Figure 3 which depicts the ballistic properties of a single plate material, heat treated to a series of hardness values, and tested under two different ballistic conditions.[4] It will be noted that the .50 caliber testing indicates an increasing resistance to penetration with increasing hardness up to a certain limiting hardness, beyond which the penetration resistance rather abruptly decreases. This is the characteristic pattern of the relationship between penetration resistance and hardness.

At hardness values below the limiting hardness, the behavior is completely ductile; the plate material is simply pushed aside by the projectile and on complete penetration ordinarily no plate material is lost. The energy absorption is entirely by plastic flow and the penetration resistance is dependent largely upon the stress level at which this plastic flow occurs which is determined by the hardness.

At hardness values which are above this limiting value, however, the behavior is no longer completely ductile. At these higher hardnesses the plastic flow is decidedly restricted and plate material may be lost by spalling during a complete penetration. This limitation of the plastic flow results, of course, in a lower energy absorption and the penetration resistance correspondingly decreases.


NFG PHOTO NO. 943 (APL)
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VARIATION OF LIMIT VELOCITY WITH BRINELL HARDNESS
FOR 1/2" HIGH CARBON HOMOGENEOUS LIGHT
ARMOR. VS. .50 CAL. AND .30 CAL. A.P. M2
BULLETS AT 0° OBLIQUITY
.30 CAL. AP M2
.50 CAL. AP M2
CORRECTED LIMIT VELOCITY (ft./sec.)
2800
2600
2400
2200
2000
1800
1600
1400
250
300
350
400
450
500
BRINELL HARDNESS

FIGURE 3

This limiting hardness for a given material and set of testing conditions is known as the optimum hardness and represents, as just described, a critical toughness value. Furthermore, the ballistic performance at this optimum hardness is primarily determined by the toughness of the plate material. This implies that homogeneous armor improvement studies should be concerned primarily with the factors governing toughness and that the results of such studies can be quantitatively evaluated on the basis of ballistic testing at optimum hardness for the given ballistic conditions with the assurance that factors so evaluated will apply qualitatively to other ballistic conditions. This viewpoint considerably simplifies the planning and execution of such studies.

II. Effect of Ballistic Conditions

As mentioned above, the apparent ductility is affected by the pattern of the combined applied stresses, by the rate of application of these stresses and by the temperature. The general effect of combined stresses is to decrease the ductility or to decrease the maximum strength level for ductile behavior. For example, a material which behaves in a ductile manner in simple tension may behave in a brittle manner when a restraint is imposed in the transverse direction so that it is subjected to biaxial tension.[5]

The pattern of the combined stresses applied to the armor is largely determined by two factors: (1) The ratio of the thickness of the plate to the diameter of the projectile, (customarily designated as e/d) and (2) the obliquity or the angle of attack (customarily designated as θ). The ballistic behavior, and the optimum hardness for maximum penetration resistance is markedly affected by these factors. The general effect of decreasing the e/d ratio (increasing the size of projectile attacking a given plate) is to decrease the apparent ductility or to decrease the optimum hardness. The general magnitude of the effect on optimum hardness is illustrated in Figure 4 taken from the work at the Naval Proving Ground under Technical Project No. 79.[4]

The effect of increasing the obliquity is likewise to decrease the ductility or optimum hardness. Thus, a much harder plate would be used to resist a normal attack than would be used for attacks at 30° to 40° obliquity. This effect has not however been quantitatively evaluated to the same extent as the effect of the e/d ratio.

The general effect of increasing the rate of loading is also to decrease the ductility. This is however, very difficult to evaluate as the striking velocities are so closely interrelated with the other variables, e/d and obliquity, that it is very difficult to isolate the velocity effect itself. This effect has nevertheless been used by the Naval Research Laboratory to evaluate armor compositions and metallurgical factors. The N.R.L. test is known as a "finger test" and involves shooting off a standard notched sample or "finger" as in an Izod impact test but using a blunt projectile from a .50 caliber gun to furnish the impact. The results are evaluated in terms of the limit velocity required for complete fracture and it is found that inferior materials fracture in a brittle manner at a relatively low velocity on this test.

Ductility is also decreased by lowering the temperature. In fact it is now a common practice to designate ductility in terms of the temperature at which the fracture behavior changes from ductile to brittle on a notched impact test. This furnishes an indication of the effect of temperature on ductility under combined stresses and, while it cannot be correlated directly with armor performance, it does furnish a much better comparative evaluation than the room temperature impact values alone.

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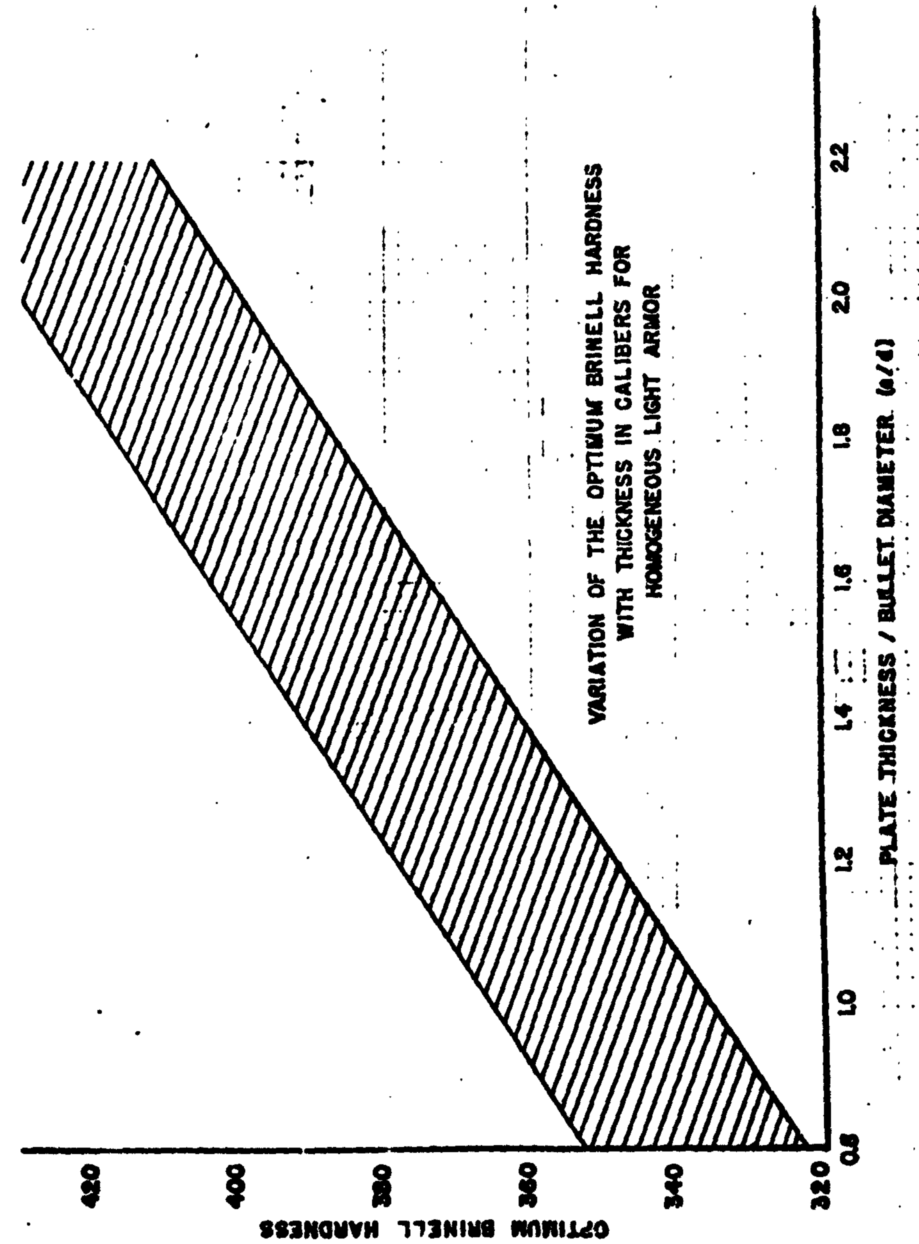


FIGURE 4

The effect of temperature on ballistic performance can best be illustrated by the tests carried out at Camp Shilo, Canada in January and February of 1943. Homogeneous armor plates in thicknesses of 1", 1-1/2" and 2" were tested at Camp Shiloh at temperatures of from -15° to -35° F. Many plates which performed satisfactorily on room temperature tests, cracked or spalled on the specification shock test at these lower temperatures.

At this point it should be mentioned that since most of the experimental work and acceptance testing of aircraft armor has been based on ballistic tests with armor piercing projectiles at normal obliquity, most of the ballistic results quoted and referred to in this report are on this basis although in service oblique attack or attacks with high explosive projectiles are much more probable than this condition. With the viewpoint expressed in the section on the effect of hardness in mind, however, this is not as serious as it might at first seem. As pointed out in that section, the ballistic behavior at optimum hardness is primarily dependent upon the toughness of the plate material for any given set of ballistic conditions and the factors governing toughness can therefore be evaluated in terms of ballistic properties under the conditions of a normal attack with an armor piercing projectile with the assurance that the same factors will govern the behavior under oblique attack or attacks by high explosive projectiles. The optimum hardness, to be sure, will vary with the ballistic conditions and it will be obvious from this summary that further work is needed to establish these optimum ranges for the various ballistic conditions. The factors governing toughness, however, which are the fundamental answers which will apply to the ballistic performance of homogeneous armor regardless of the ballistic conditions can be satisfactorily evaluated on the basis of these ballistic tests at optimum hardness with armor piercing projectiles of normal obliquities and such an evaluation is the primary aim of homogeneous armor improvement studies.

Metallurgical Factors

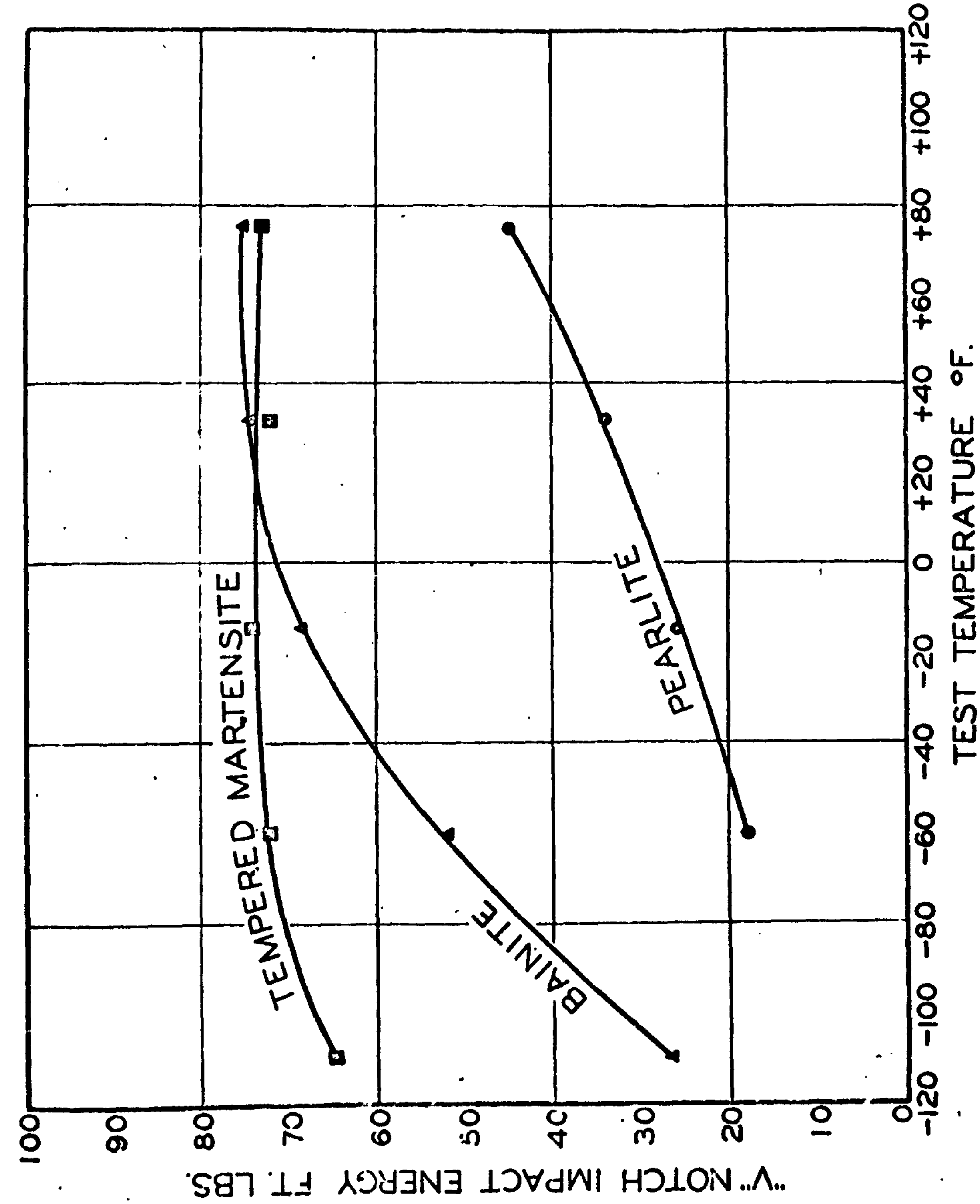
I. General

The principal metallurgical factors affecting the performance of homogeneous aircraft armor are: (1) microstructure, (2) heat treatment, (3) composition and (4) homogeneity. These are all interrelated and their effects are often difficult to isolate either in practice or in discussion. For example, the choice of a composition involves consideration of its hardenability or its ability to give the desired microstructure, of its effect on the tempering behavior and on temper brittleness and finally of specific effects of the carbon content and alloying elements. In addition, the "cleanliness" or freedom from non-metallic inclusions may be influenced by the composition. Thus, all of the other variables, microstructure, heat treatment and homogeneity may be involved in the choice of a composition or in considering the effects of composition. In general however, the primary variable is microstructure and the other factors may be considered as modifying the properties or the performance of steels of the optimum microstructure.

II. The Effect of Microstructure

A. Pure Microstructures - Tempered Martensite, Bainite and Pearlite

The optimum microstructure for homogeneous armor is tempered martensite. Its superiority has been established beyond doubt both on the basis of ballistic performance and mechanical and impact properties. This is illustrated in Figure 5 taken from the work of Queneau and Pellini at the Naval Proving Ground.[6] This shows the comparative impact properties as a function of the testing temperature for the same steel, heat treated to tempered martensite, bainite, as formed at 600° F. and pearlite, as formed at 1100° F. The tempered martensite and bainite



"V" NOTCH IMPACT ENERGY FT. LBS.
100
90
80
70
60
50
40
30
20
10
0
TEST TEMPERATURE °F.
−120
−100
−80
−60
−40
−20
0
+20
+40
+60
+80
+100
+120
TEMPERED MARTENSITE
BAINITE
PEARLITE

FIGURE 5

are at essentially the same hardness (220 Brinell) and the pearlite is at a somewhat lower hardness (200 Brinell). The superiority of tempered martensite is evidenced not only by its higher impact values at room temperature but by its lower "transition temperature", that is, by its retention of ductility at low temperatures. This superiority would be expected to be reflected in ballistic performance.

The inferior toughness of pearlitic microstructures has been so well established that such structures are never used for armor. Comparative tests have, however, been made of lower bainite and tempered martensite and generally very little difference has been found in their ballistic performance. This is illustrated in Figure 6 taken from work at the Naval Proving Ground.[4] This shows the ballistic performance as a function of hardness for plates of the same composition, quenched and tempered to tempered martensite and austempered to lower bainite. It is, however, important that this bainite be formed at a low temperature, near that at which transformation to martensite begins, as the upper bainite microstructures, formed at the higher temperatures, are distinctly inferior.[7]

B. Mixed Microstructures

If the quenching rate is too slow or if the steel is lacking in hardenability, the transformation to martensite on cooling will be preceded by a prior transformation to higher temperature transformation products and a mixed microstructure will result.[8] These mixed microstructures will always have poorer properties than full tempered martensite and are therefore undesirable.

The non-martensitic products in these mixed microstructures may be proeutectoid ferrite or carbide, upper bainite or pearlite, and the properties depend upon both the nature and amount of these products. In the opinion of

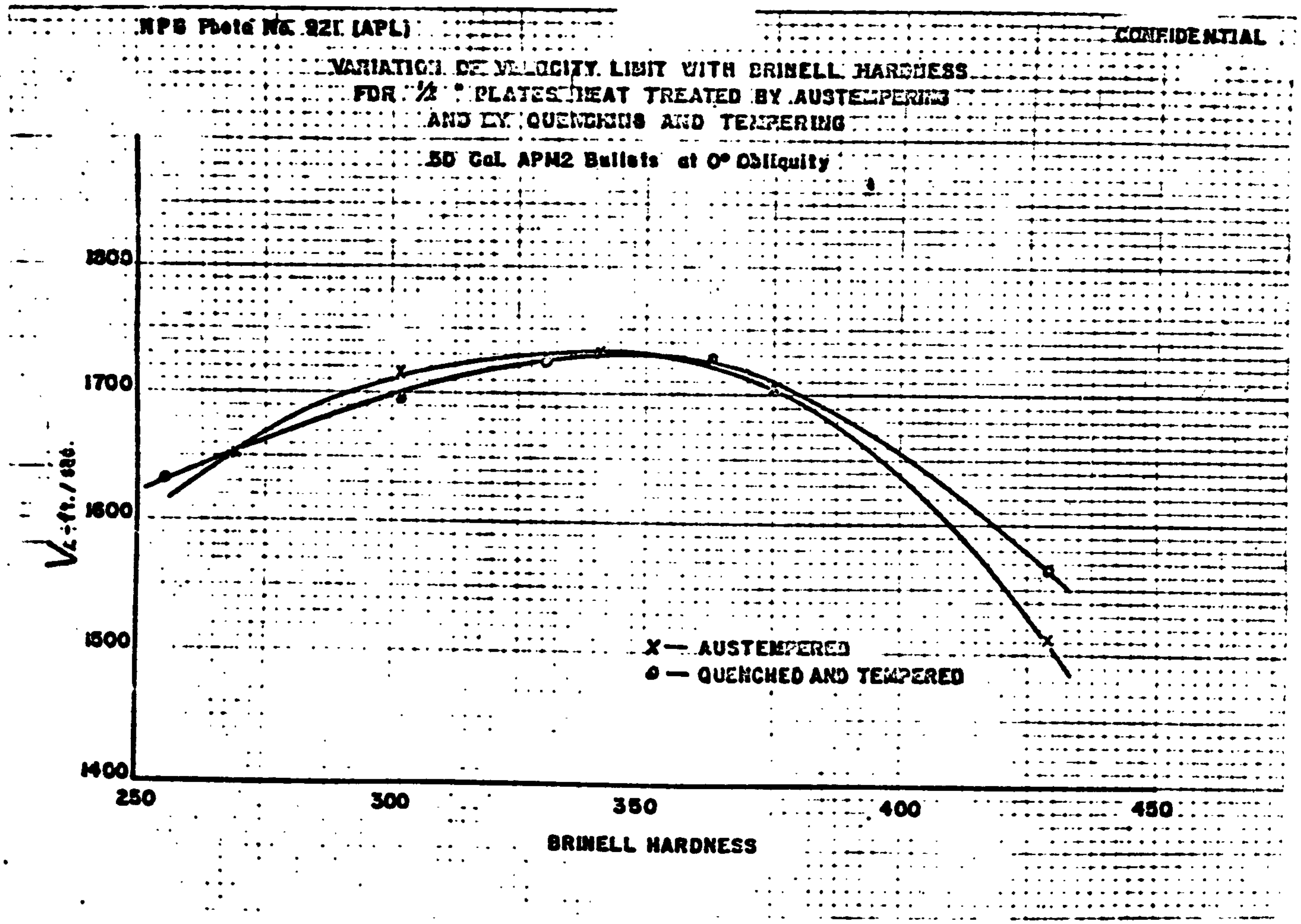

NPS Photo No. 921 (APL)
CONFIDENTIAL
VARIATION OF VELOCITY LIMIT WITH BRINELL HARDNESS
FOR ½" PLATES HEAT TREATED BY AUSTEMPERING
AND BY QUENCHING AND TEMPERING
.50 Cal. APM2 Bullets at 0° Obliquity
V_L-ft./sec.
1400
1500
1600
1700
1800
250
300
350
400
450
BRINELL HARDNESS
X — AUSTEMPERED
o — QUENCHED AND TEMPERED

FIGURE 6

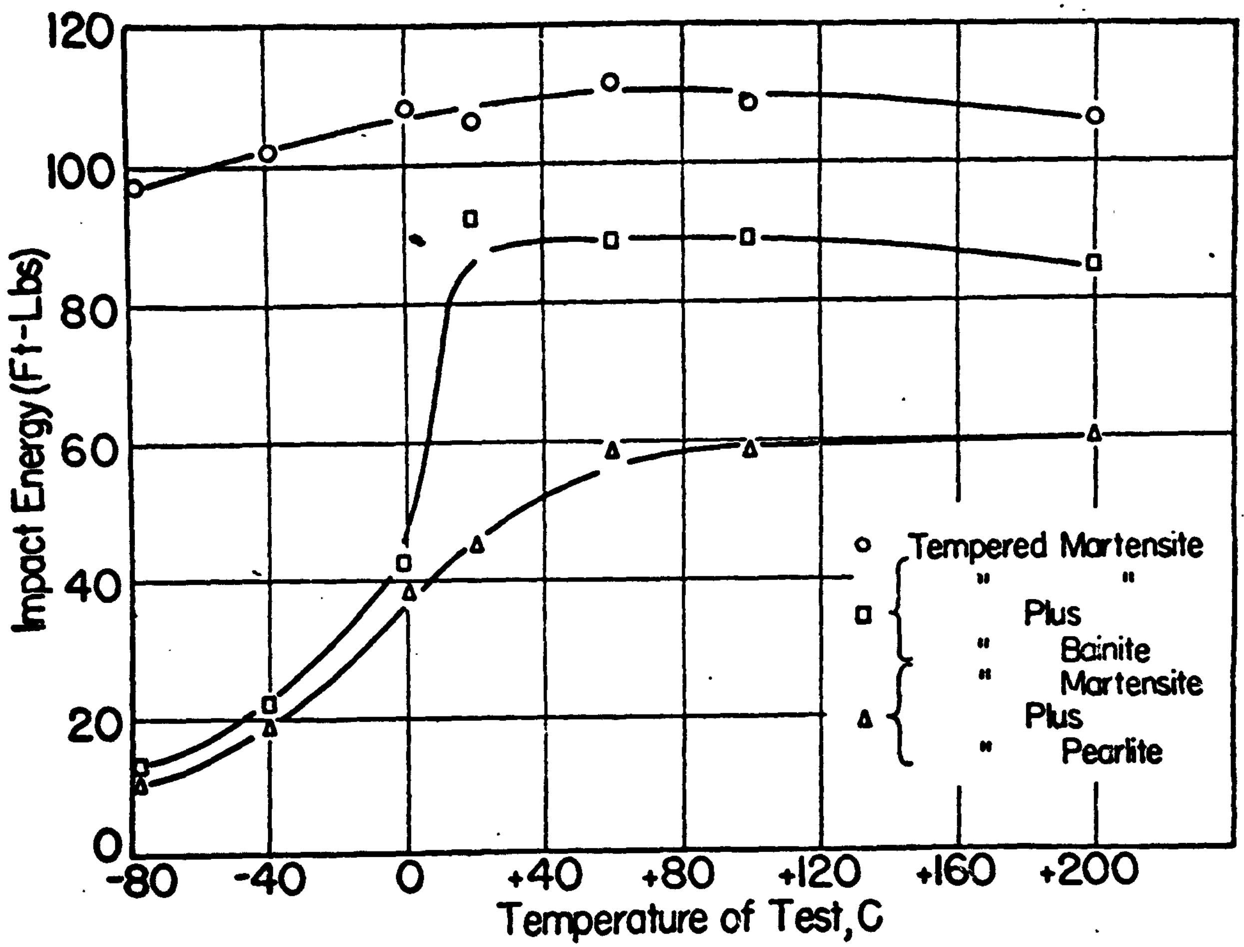
the authors, in the hardness ranges usually used for homogeneous aircraft armor, pearlite is the most harmful, upper bainite next and ferrite the least harmful of these products. Most homogeneous armor compositions are hypo-eutectoid so that pro-eutectoid carbides will not usually be present but this constituent is decidedly harmful, particularly if it occurs at the grain boundaries. It is likewise unusual to find pearlite as a constituent of these structures in the relatively high alloy compositions ordinarily used for homogeneous armor since the transformation rates in the pearlite temperature range are generally very slow in such alloy steels. The non-martensitic products in these steels are therefore generally either ferrite or upper bainite.

The effects of these non-martensitic products have not been quantitatively evaluated in terms of ballistic performance or mechanical properties as a function of the percentage of the non-martensitic product but their deleterious effect in general has been established by many tests.

The effect of non-martensitic products on notch impact is illustrated by Figure 7 taken from the work of Hollomon and Jaffe at Watertown Arsenal.[9] The inferior properties of the mixed microstructures are evidenced not only by their lower impact values at room temperature but by their higher "transition temperature"; that is, the tempered martensite retains its ductility to much lower temperatures than do the mixed structures. The distinct inferiority of the tempered martensite-pearlite mixture is also indicated by this illustration. These inferior notch impact properties would presumably be reflected in inferior ballistic performance.

These effects of non-martensitic products on mechanical and ballistic properties have been systematically investigated for the N.D.R.C. by Lorig and Associates at Battelle as part of a study of the "Correlation of Metallographic Structures and Hardness Limit in Armor Plate".[10] In this work, 1/2" plates

MICROSTRUCTURE AND PROPERTIES OF STEEL



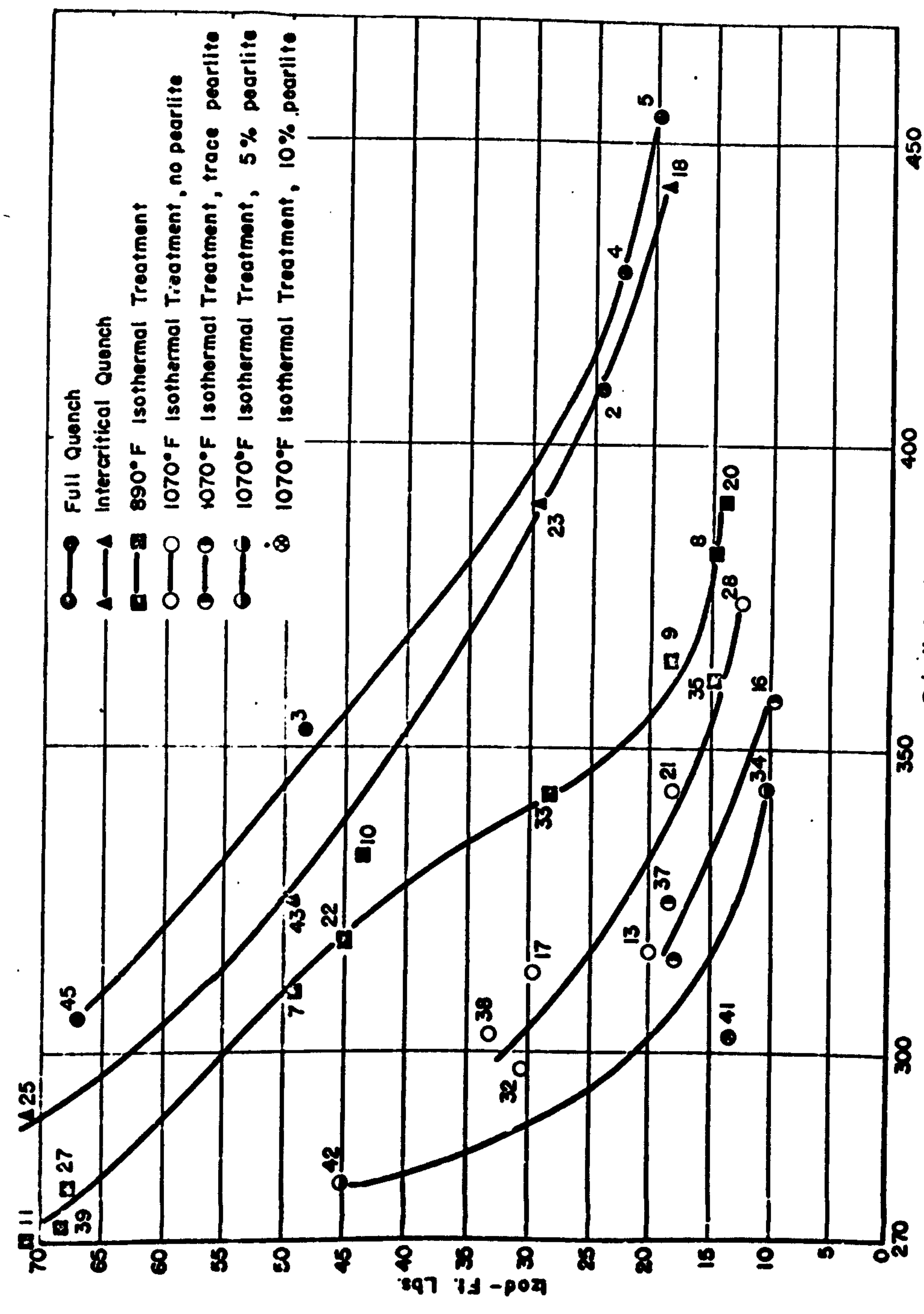
Impact Properties of Steels of Various Structures at a Tensile Strength of Approximately 125,000 psi.

FIGURE 7

were heat treated to various mixtures of tempered martensite, pearlite, upper bainite and ferrite and tested ballistically at Watertown. The impact properties of these plates as a function of hardness is shown in Figure 8, while their ballistic properties are summarized in Figure 9. The full quench and temper treatment resulted in essentially tempered martensite and was in general superior in impact and ballistic properties. The intercritical quench resulted in a mixture of tempered martensite and ferrite and this mixture was only slightly inferior in impact properties and showed no inferiority in ballistic limit at a given hardness but had a greater tendency to back spalling. The 1070° F. isothermal treatment resulted in mixtures of tempered martensite, ferrite and fine pearlite, and those structures which contained appreciable amounts of pearlite were found to be decidedly inferior in both impact and ballistic properties. The 890° F. isothermal treatment resulted in a mixture of tempered martensite and upper bainite and its impact and ballistic properties were intermediate between those of the tempered martensite and those containing pearlite.

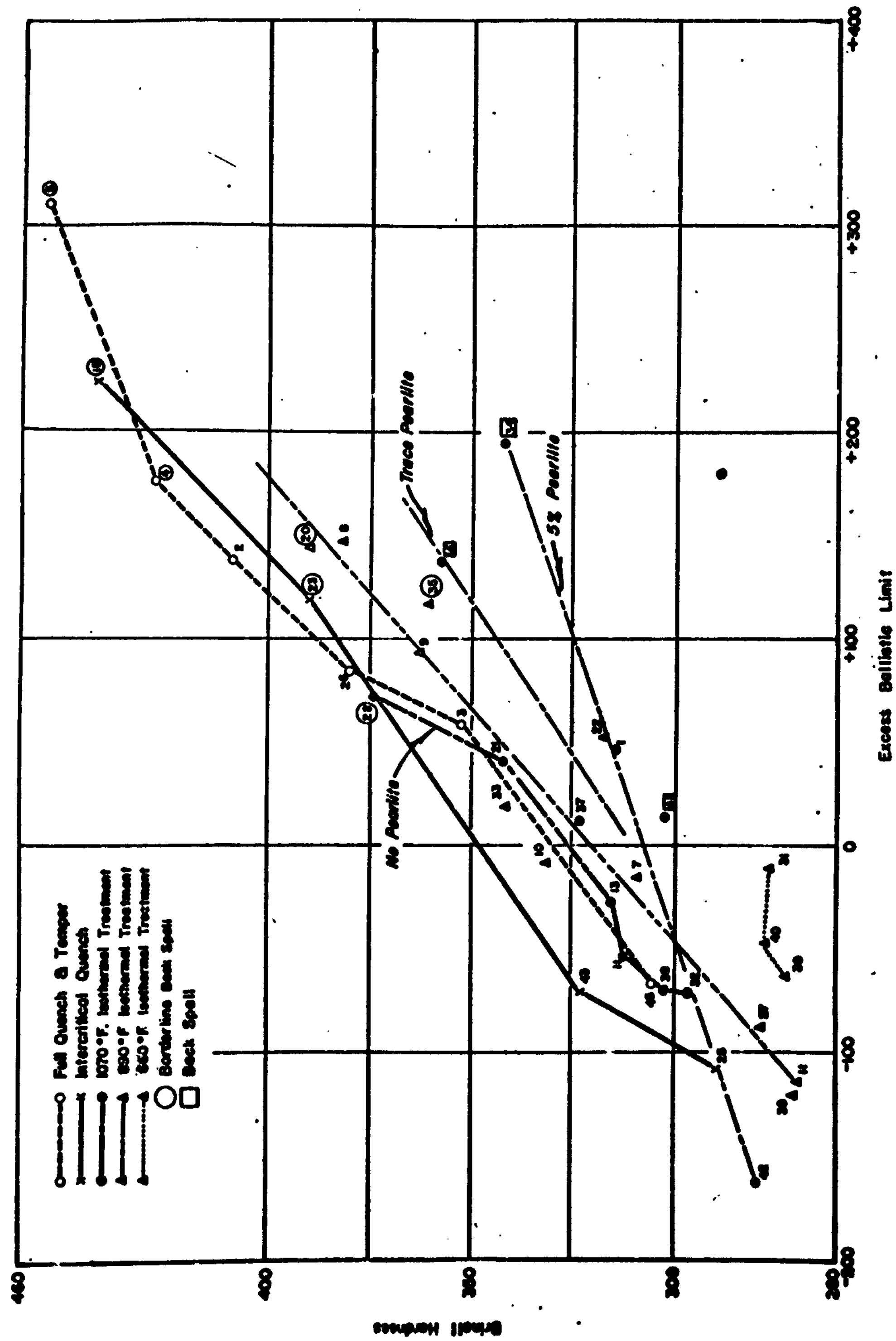
The effect of microstructure is further illustrated by the results of a thorough metallurgical examination of the plates which were tested at low temperatures at Shilo, Canada. This examination was carried out at Watertown Arsenal.[11]

It was found in this study that the plates which spalled or failed the shock test were characterized by a mixed microstructure of tempered martensite and high temperature transformation products (ferrite and upper bainite), while the plates which were successful on these tests showed essentially full tempered martensitic structures. A typical microstructure of a plate which showed poor performance on this test is shown in Figure 10 while the tempered martensitic structure of a typical successful plate is shown in Figure 11.



BRINELL HARDNESS VS. IZOD VALUE FOR ARMOR STEELS GIVEN VARIOUS HEAT TREATMENTS.

FIGURE 8

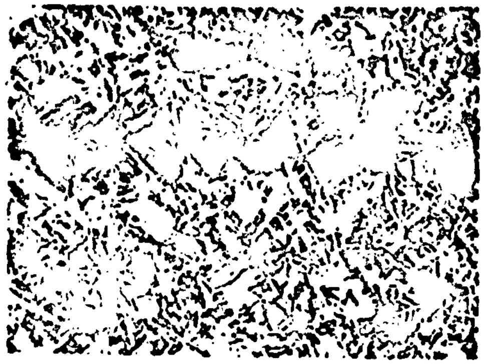


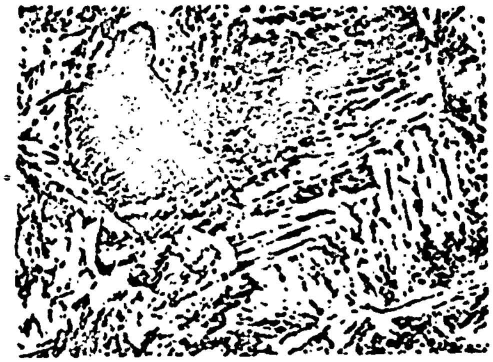
HARDNESS VS BALLISTIC PROPERTIES OF ARMOR PLATE GIVEN VARIOUS HEAT TREAT

FIGURE 9

1½" Plate No. 1X4

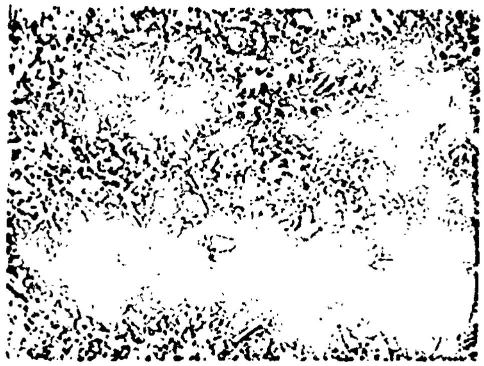
(Microspecimen etched with 4% Picral)





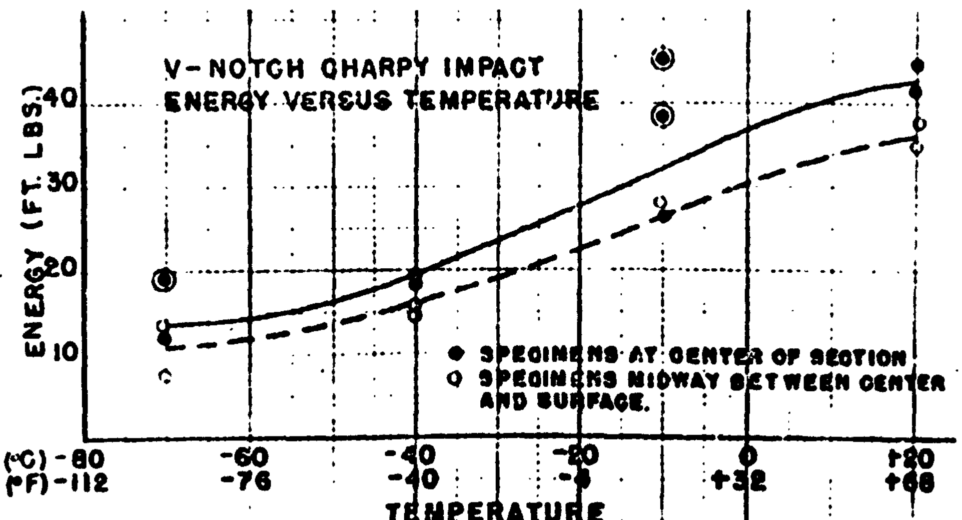
X200 **Center of Section** X1000

Moderate banding - Typical field shows tempered martensite and a great deal of tempered non-martensitic transformation products.



X200 **Midway Between Surface and Center** X1000

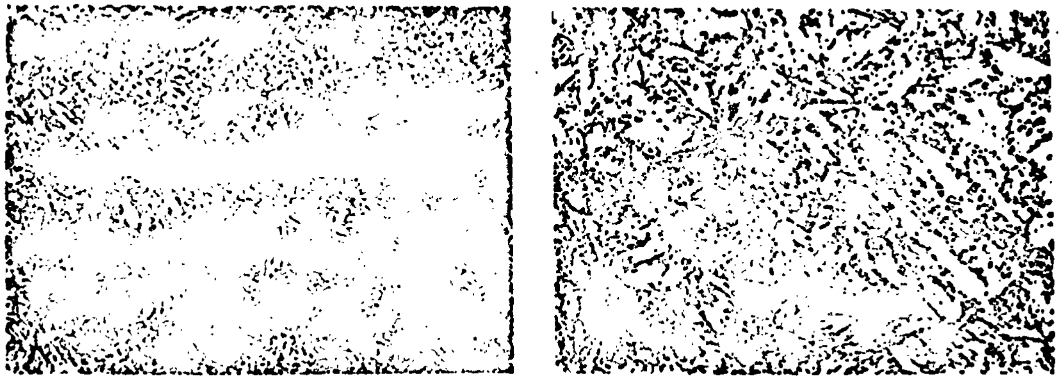
Slight banding - Typical field shows tempered martensite and some tempered non-martensitic austenite decomposition products.



NOTE: ◉ SIGNIFIES THAT CHARPY SPECIMEN CONTAINS A DEEP LAMINATION

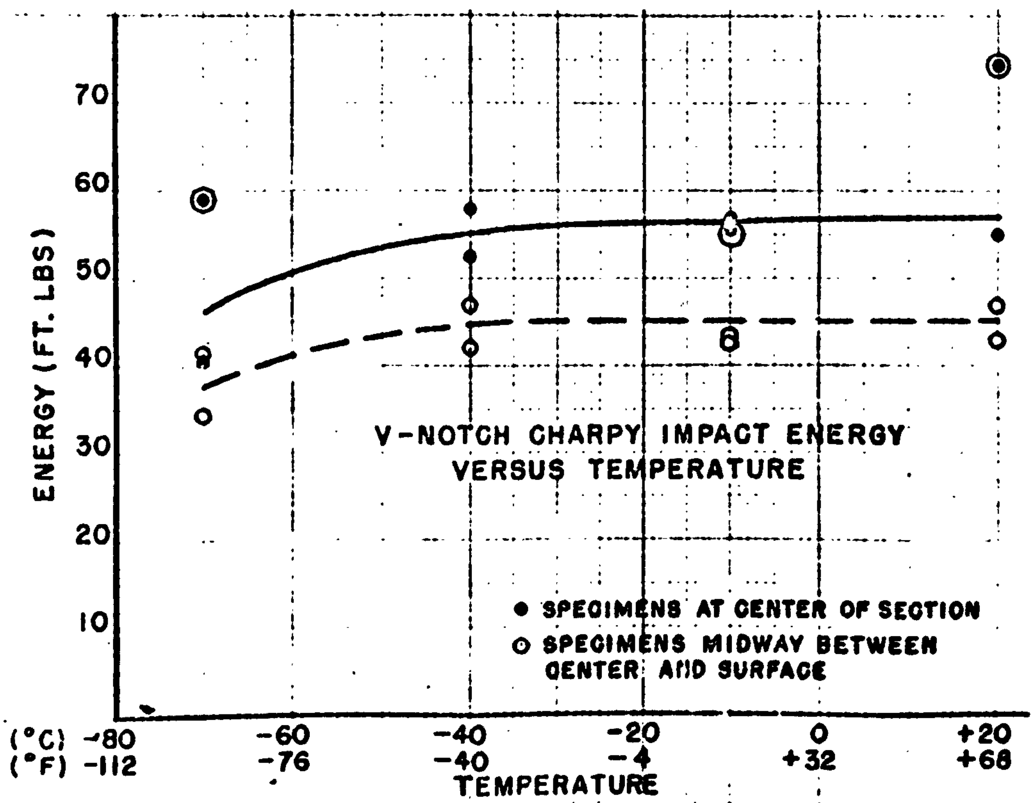
FIGURE 10

1½" Plate No. M1X3
(Microspecimen etched with 4% Picral)



X200 Center of Section X1000

Moderate banding - The structure throughout the section consists of acicular tempered martensite.



NOTE: ◉ SIGNIFIES THAT CHARPY SPECIMEN FRACTURE CONTAINS A DEEP LAMINATION

FIGURE 11

The deleterious effect of grain boundary carbides was mentioned above. This condition may occur in some of the higher carbon and alloy compositions if improperly heat treated. The effects of this condition are illustrated in a Watertown Report[12] which pointed out that carbides at the grain boundaries (as revealed by the Murakami etch) tended to produce spalling and by a Naval Proving Ground Report[13] which showed that a segregation of small undissolved carbides in 1/4" homogeneous plates, resulting from improper heat treatment, had resulted in a poor ballistic performance against the 20mm H.E. projectile.

III. Effect of Inhomogeneities

A. General

Homogeneous aircraft armor should, ideally, be truly homogeneous, as any inhomogeneities will decrease its effectiveness. The above discussion of the effects of microstructure has pointed out the general harmful effects of inhomogeneous microstructures such as mixtures of tempered martensite and upper transformation products and the desirability of a uniform tempered martensitic microstructure. In addition to this microstructural inhomogeneity, inhomogeneities such as laminations, non-metallic inclusions, segregation and banding may be present in homogeneous armor. As a matter of fact, since segregation invariably results during the solidification of ingots and since the deoxidation of the steel invariably produces oxides which become non-metallic inclusions, completely homogeneous armor is impossible. Furthermore, the process of hot rolling changes the distribution of these inhomogeneities and thereby imparts directional properties to the plates and unless this is carefully controlled, an anisotropy of properties will result. Thus, a certain amount of inhomogeneity will always be present and the aim must be to minimize these inhomogeneities and their harmful effects rather than to completely eliminate them.

B. The Effects of Laminations

The term lamination ordinarily refers to any separation which is visible on the cross section to the unaided eye. The most common cause of lamination of course is "piping" or insufficient cropping so that the shrinkage cavity remains in the plate. Laminations may also result from severe segregations of non-metallic inclusions or from "flaking". The effects of non-metallic inclusions will be discussed in the next section. "Flakes" which are internal cracks formed ordinarily during cooling from rolling are fortunately rather infrequently encountered in aircraft armor since the plates are generally relatively thin and the cooling stresses are low.

The effects of these actual separations or laminations would certainly be quite serious but as indicated above, such drastic inhomogeneities are infrequent and their effect in aircraft armor has not been quantitatively evaluated in terms of ballistic performance.

C. The Effects of Non-Metallic Inclusions

In general, non-metallic inclusions tend to increase spalling and to lower the optimum hardness for best ballistic performance under a given set of conditions. The magnitude of the effect, however, will vary with the amount, the nature, the size and the distribution of the inclusion particles. Plastic inclusions, which become elongated during rolling, are ordinarily more harmful than the more refractory inclusions such as alumina which tend to remain in small disjoined particles. These latter types of inclusions may however be quite harmful if they are in clusters which are lined up into "stringers" during rolling.

A quantitative evaluation of the effect of non-metallic inclusions on ballistic performance is reported in a Naval Proving Ground Memorandum[14] which will serve as an illustration of their effect. This memorandum reported on an investigation of ballistic failures of light armor plate. The inclusion contents of 1/4" plates were rated by measuring the total length of inclusions over 1/2" in length at 200X magnification, measured along the center line of ten fields each six inches square at this magnification. All samples were longitudinal to the direction of rolling. Representative fields and their count are shown in Figure 12. The correlation of this count with spalling tendency as determined by the diameter of the exit hole is shown in Figure 13. The correlation with ballistic performance on the 20mm H. E. shock test is shown in Figure 14. It will be seen that the correlation is very good; the "dirtier" steels showing markedly larger exit holes and lower resistance to 20mm H. E. projectiles.

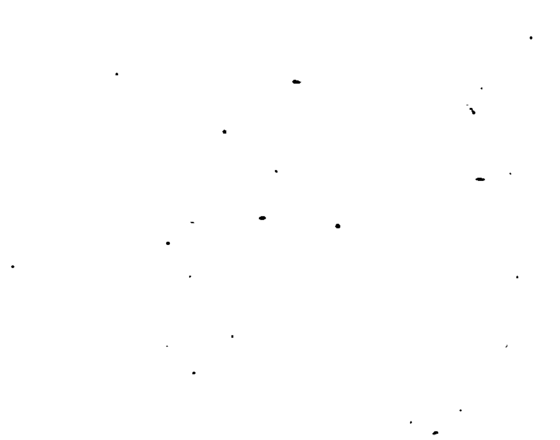
D. The Effect of Banding

The segregation of carbon and the alloying elements during solidification and cooling of the ingot will be reoriented during the hot working process so that the final plates will show a micro-segregation or banding, parallel to the final rolling direction. The harmful effect of this banding results principally from the fact that some of these bands will have a low carbon and alloy content and consequently a low hardenability. Therefore, unless a sufficiently drastic quench is used to insure full transformation to martensite in these low hardenability bands, high temperature transformation will occur in these bands and an undesirable microstructure will result. If the heat treatment is properly adjusted to insure transformation to full martensite in these bands, however, banding will not ordinarily be particularly harmful.

RATING OF INCLUSIONS (DIRT CHART) FOR 1/4 INCH LIGHT ARMOR

DIRT COUNT 8

DIRT COUNT 113



DIRT COUNT 51

DIRT COUNT 153

DIRT COUNT REPRESENTS THE EQUIVALENT NUMBER OF 1/2 INCH INCLUSIONS FOUND IN 10 FIELDS AT 200X. PHOTOMICROGRAPHS AT 200X, UNETCHED.

DIRT COUNT 222

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NPG PHOTO NO. 1684 (APL)
JUNE 16, 1944

FIGURE 12

CONFIDENTIAL NPG PHOTO 24956

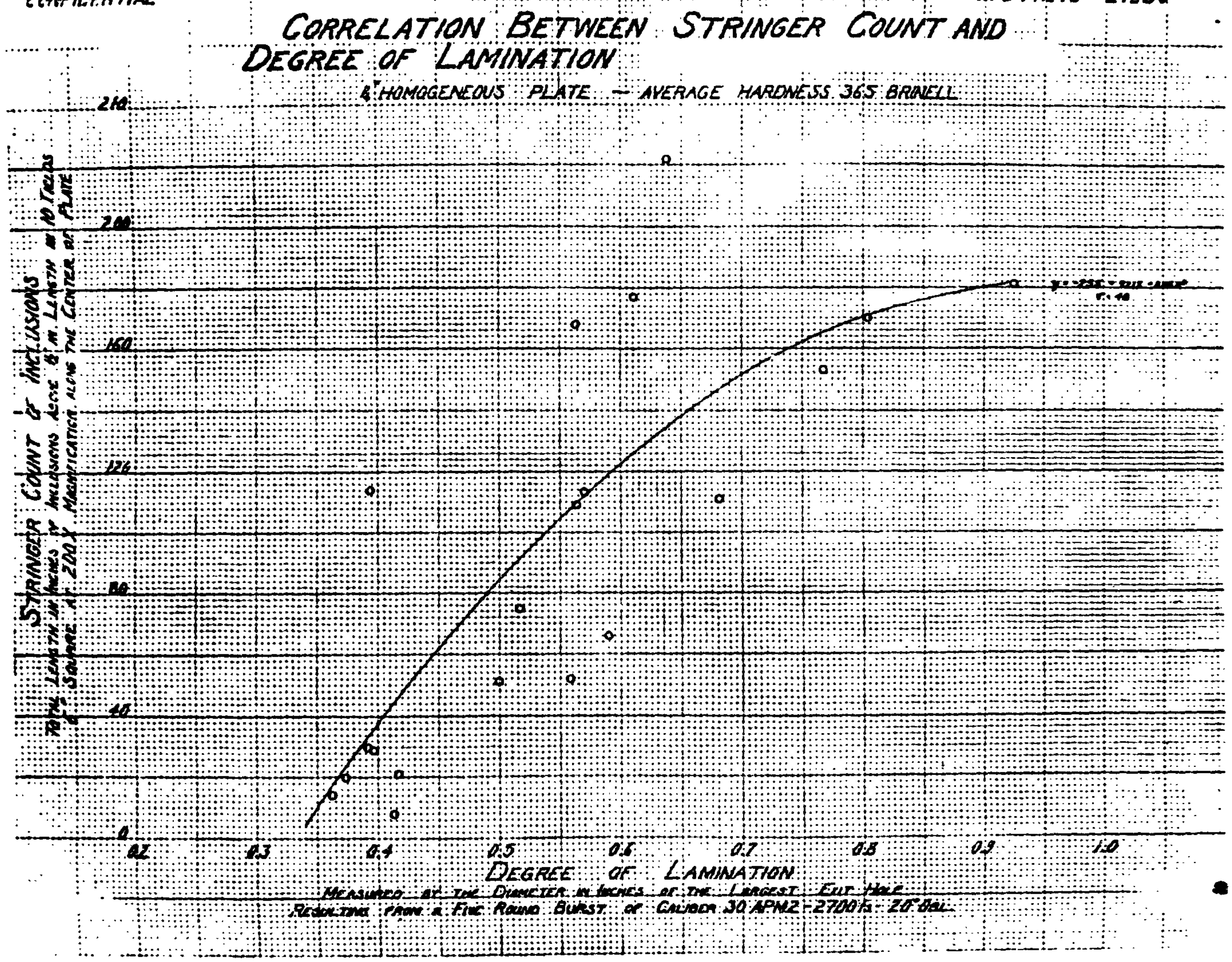


FIGURE 13

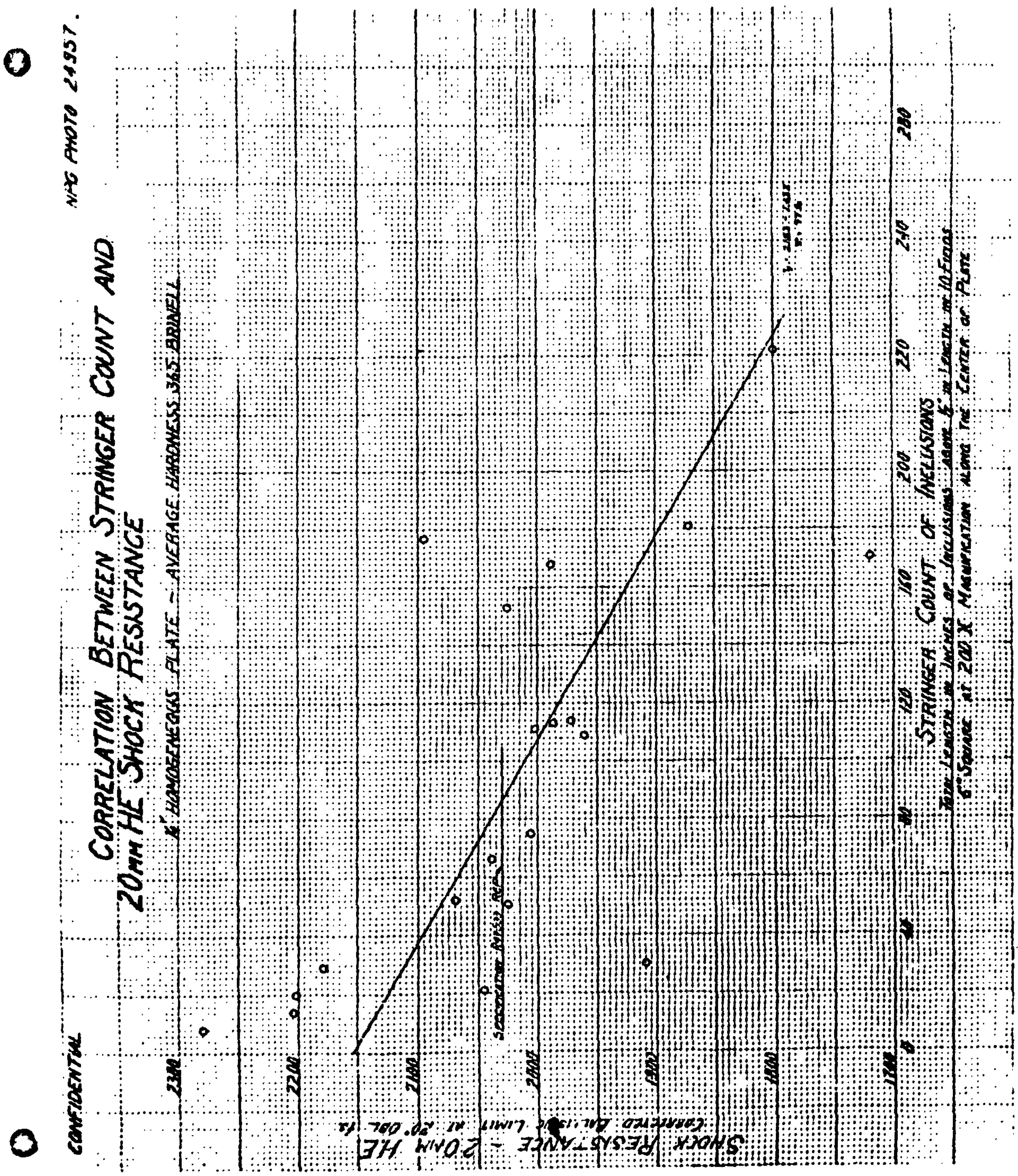

NPG PHOTO 24957.
CONFIDENTIAL
CORRELATION BETWEEN STRINGER COUNT AND
20MM HE SHOCK RESISTANCE
HOMOGENEOUS PLATE – AVERAGE HARDNESS 363 BRINELL
SHOCK RESISTANCE – 20MM HE
STRINGER COUNT OF INCLUSIONS
2300
2200
2100
2000
1900
1800
1700

FIGURE 14

E. The Effect of Hot Working and the Direction of Rolling

As mentioned above, hot working results in a reorientation of the inclusions and segregated areas so that the final plate may have marked directional properties dependent upon the relative amounts of hot working in the transverse and longitudinal directions with respect to the original ingot. Plates which have been "straightaway" rolled, that is, in which all of the rolling has been parallel to the longitudinal direction of the original ingot, exhibit marked differences in ductility in the transverse and longitudinal directions; the transverse properties being distinctly inferior. Such plates will show corresponding differences in ballistic performance depending upon the relation between the angle of attack and the rolling direction. They will also tend to split longitudinally under a high explosive impact and their resistance to such an attack will be low.

In order to offset these defects, plates should be cross rolled; that is, the hot working should include reductions in both the longitudinal and transverse directions and if possible the transverse and longitudinal reduction should be approximately equal in order to equalize the properties in each direction. Mill limitations may often preclude the attainment of this ideal condition of fifty per cent of the reduction in each direction, however, but this should be approached as closely as possible within these limitations.

Many cases of poor ballistic performance from insufficient cross rolling have been noted, but the effect has not been systematically investigated.

IV. The Effect of Heat Treatment

A. General

Since, as indicated above, the first requisite of good homogeneous armor is a suitable microstructure, the heat treatment must, first of all, be aimed at the attainment of the desired microstructure. The usual heat treatment is a quench and temper treatment and the desired microstructure is full tempered martensite. In order to insure the attainment of the full martensitic microstructure, the austenitizing and quenching practice must be properly planned and carefully controlled, and, as will be discussed later, in order to insure optimum properties, the tempering operation must likewise be planned with the particular application of the plate in mind and must also be carefully controlled.

B. Austenitizing

In planning the austenitizing treatment, first consideration must be given to the attainment of full carbide solution and a homogeneous austenite in order that full advantage may be taken of the hardenability effects of the alloying elements. The austenitizing temperature and time must therefore be sufficient to accomplish this result but not so high as to result in a pronounced grain growth. Some of the higher carbon, higher alloy steels may require rather high temperatures of the nature of 1650-1750° F. to accomplish this result. Along with these higher temperatures goes a greater danger of decarburization during the austenitization and this must be guarded against by use of a protective atmosphere or other suitable protective measures.

The solution of carbides in heating for quenching may often be facilitated by a pretreatment consisting of a normalize from a relatively high temperature which will insure complete solution of the carbides and their precipitation as relatively fine particles which are more readily soluble during the final heating for quenching. This pretreatment is practically a necessity for the higher carbon, high alloy materials and may or may not be necessary for the lower carbon and alloy compositions.

Examples of the deleterious effects of incomplete carbide solution are reported in a Watertown Arsenal Report(15) and in a Naval Proving Ground Memorandum.(13) The Watertown report showed that a retreatment of 1", 0.50% carbon, high alloy plates markedly improved the ballistic performance. This retreatment was primarily aimed at obtaining a complete solution of carbides and included a preliminary high temperature normalizing treatment prior to the quench.

The Naval Proving Ground memorandum compared the ballistic properties of 1/4" plates of the same composition, heat treated by two different companies, using different practices. The ballistic performance of the plates which were normalized and quenched from the higher temperatures with resultant better carbide solution were markedly superior.

C. Quenching

The quench must first of all be rapid enough to obtain full martensite without prior transformation to higher temperature transformation products. The choice of the quenching medium will be determined by the composition of the steel and the limitations in regard to distortion and cracking. Oil quenching is the most common for the relatively high carbon and high alloy materials customarily used for aircraft armor. Some means of agitation, such as pumps or propellers, should be used to insure the necessary rapid and uniform quenching. Quench cracking is a serious problem in these materials and in order to minimize this tendency, plates should be quenched only to a temperature low enough to insure essentially complete transformation to martensite and should be tempered immediately after quenching.

D. Martempering

An alternative quenching method which is helpful in reducing the tendency to distortion and cracking is that of "martempering". This procedure involves quenching into a salt or molten metal bath at a temperature near that at which transformation to martensite begins (the M_s Temperature) holding at this temperature long enough to equalize the temperature throughout the plate and then air cooling to room temperature. Since the temperature is equalized throughout the piece and the cooling through the martensite temperature range is relatively slow, the formation of martensite is accompanied by much less stress than in the usual practice of quenching through this temperature range, and the distortion and danger of cracking is thereby greatly decreased. The method has the disadvantage of requiring steels of somewhat higher hardenability than would be necessary for oil quenching because of the lower cooling rates of the liquid baths at the martempering temperatures.

No reports are available as to the ballistic performance of plates treated by this method, but the method has been applied successfully to the heat treatment of armor piercing projectiles and would seem to offer promise as a method of heat treatment of armor.

E. Austempering

As mentioned earlier in this study, lower bainitic microstructures have properties which are generally similar to those of tempered martensite and likewise exhibit similar ballistic properties. Austempering to lower bainite, therefore, offers another alternative practice which minimizes stresses, distortion and danger of cracking. The procedure involves quenching to the austempering temperature, which should be not more than 100° F. above the M_s temperature, and holding at this temperature long enough to insure complete transformation to bainite. The plate may be quenched or air cooled from austempering and may, if necessary, be tempered to the desired hardness. Austempering also had the disadvantage of requiring a relatively high hardenability steel to prevent high temperature transformation during the cooling to the austempering temperature and the additional disadvantage that the austempering times for these relatively high hardenability steels are usually quite long and the process is therefore time consuming.

F. Tempering

The purpose of tempering is to relieve stresses and to increase ductility. In general, as the tempering temperature increases, the hardness decreases and the steel becomes more ductile. Anomalous behaviors may occur during the tempering operation, however, so that this increase in ductility is not always a continuous function of the tempering temperatures. In order that the optimum properties of the quenched and tempered steels may be attained, it is important that the general nature of these anomalous behaviors be realized even though their mechanism may not be understood.

The first of these anomalous behaviors occurs on tempering in the temperature range of from 500 to 700° F. Most alloy steels exhibit lower ductility after tempering in this range than on tempering at either higher or lower temperatures and this range should therefore be avoided.

Many of the higher alloy steels, particularly those containing the strong carbide forming elements such as molybdenum, vanadium or titanium, exhibit the phenomenon known as secondary hardening. These steels may actually increase in hardness on tempering in a certain temperature range, presumably because of a delayed precipitation of fine alloy carbides, and a marked embrittlement occurs. This temperature range will vary with the composition but is usually between 900 and 1100° F. Good ductility will again be obtained on tempering at temperatures above this range. As a matter of fact, the ductility of such steels when tempered to a given hardness at the high temperatures is generally superior to that of steels which do not contain these carbide forming elements. This is apparently a reflection of the fact that the tempering temperatures for a given hardness in steels of this type are higher than in steels without the carbide forming elements.

A third anomalous behavior on tempering is the phenomenon known as "temper brittleness". This is evidenced by a marked embrittlement (usually revealed by notched impact tests) on slow cooling from tempering temperatures of 1100° F. or above or on tempering in the range of temperatures of from about 850° to 1050° F. It is generally most pronounced on slow cooling from about 1100° F. or on reheating at about 950° to 1000° F. The susceptibility to this phenomenon varies with composition. High manganese, chromium and phosphorous contents increase the susceptibility and molybdenum tends to decrease the susceptibility. A comprehensive survey of the available information on this subject is presented in a Watertown Arsenal Report.[16] A review of this phenomenon and its relation to the heat treatment of ordnance material is presented in another Watertown Arsenal Report.[17] A further study of the phenomenon was carried out at the Naval Proving Ground and has been published as a paper for the American Society of Metals.[18] This embrittlement can be very serious in armor and the following precautions should be observed whenever possible to minimize its effect.

1. The composition should be designed to minimize the susceptibility to temper brittleness.

2. Whenever possible, within the limitations of the hardness requirements, tempering should be at temperatures above 1100° F. followed by water quenching to room temperature.

3. If it is necessary to temper in the range of 850° to 1050°F. this tempering should generally involve the shortest holding time which is practicable and should likewise be followed by water quenching to room temperature.

The effect of temper brittleness on impact is illustrated in Figure 15 taken from the work of Queneau and Pellini. It should be noted that not only is the room temperature impact value lowered by the embrittlement but that the transition temperature (the temperature of change from ductile to brittle behavior) is markedly raised.

Some of these effects of the tempering temperatures are illustrated by Figure 16 which is based on results of work at the Naval Research Laboratory. This curve shows the ballistic performance of five steels as a function of the tempering temperatures. The "P" value, which is the ordinate of this curve, is an expression of the energy absorbed during penetration at the limit velocity (cal. .50 bullets vs. 1/2" plate at 0° obliquity) and the tempering temperature is that which was used for optimum hardness. Thus, both the "P" value and the tempering temperature are representative of optimum performance. Of the five steels used in this study, three were nickel-chromium compositions at .29, .36 and .46 carbon and two were chrome-moly-vanadium compositions at .45 and .55 carbon. The lower tempering temperatures apply to the nickel-chromium steels and the higher temperatures to the chrome-moly-vanadium steels, with the steels of higher carbon contents having the higher tempering temperatures in each group. The trend toward better ballistic performance with the higher tempering temperatures is clearly indicated. It is perhaps significant, however, that the tempering temperatures for the nickel-chromium steels are all within the temper brittleness range while those for the chrome-moly-vanadium steel are above this range. The results

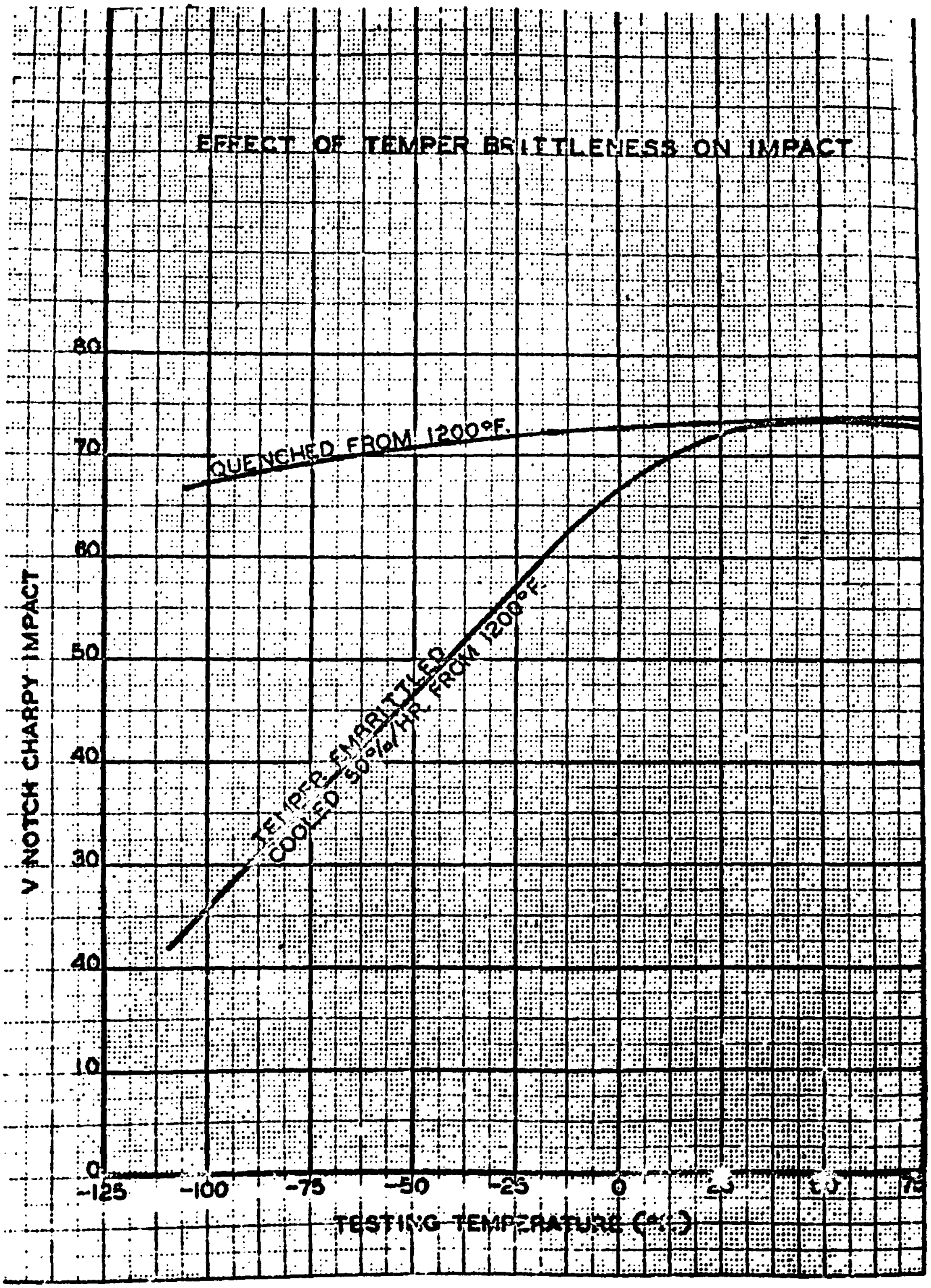

EFFECT OF TEMPER BRITTLENESS ON IMPACT
QUENCHED FROM 1200°F.
TEMPER-EMBRITTLED
COOLED 50°F/HR. FROM 1200°F.
V NOTCH CHARPY IMPACT
80
70
60
50
40
30
10
0
-125
-100
-75
-50
-25
0
TESTING TEMPERATURE

FIGURE 15

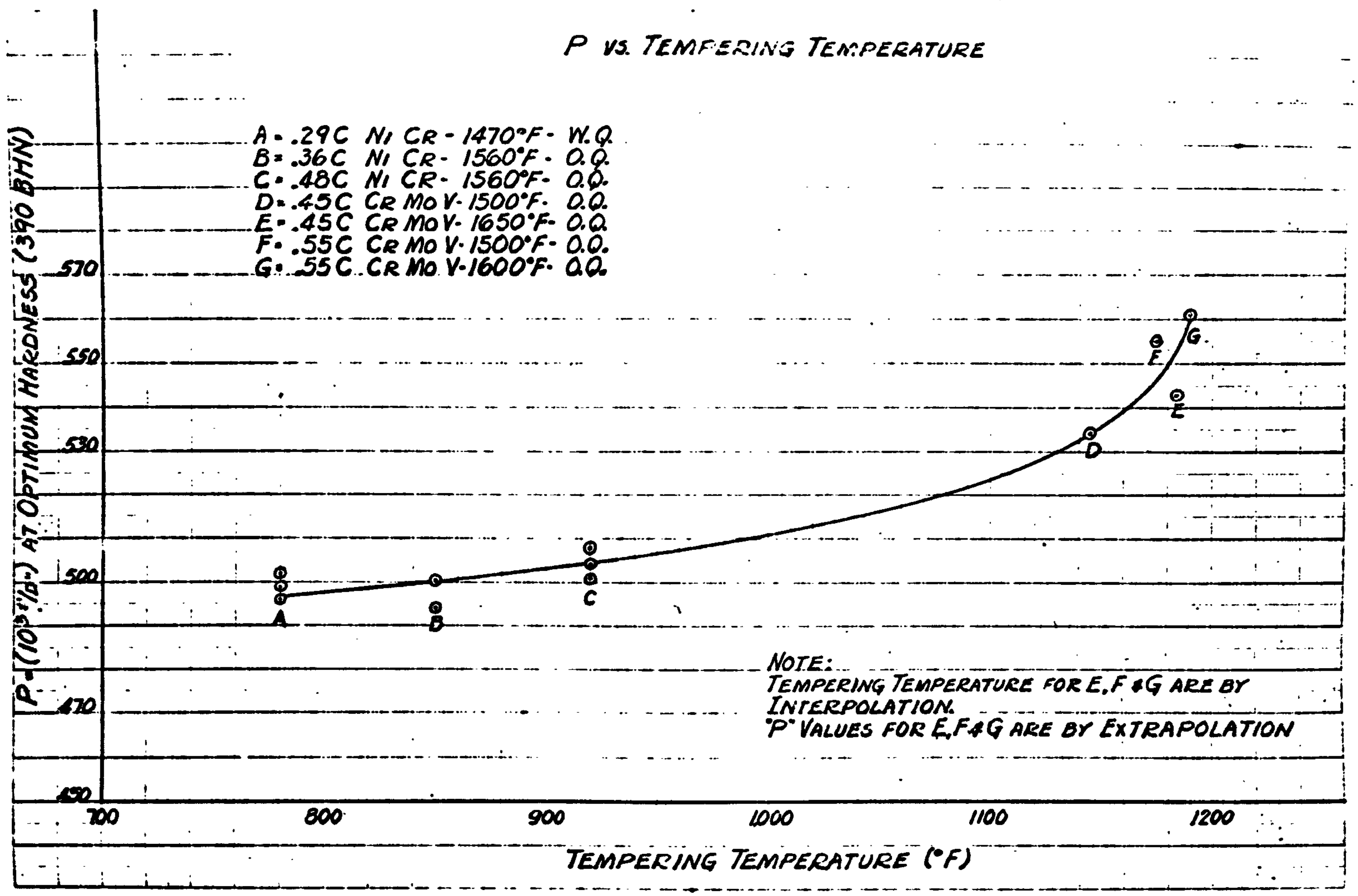

P vs. Tempering Temperature
A = .29C Ni Cr - 1470°F - W.Q.
B = .36C Ni Cr - 1560°F - O.Q.
C = .48C Ni Cr - 1560°F - O.Q.
D = .45C Cr Mo V - 1500°F - O.Q.
E = .45C Cr Mo V - 1650°F - O.Q.
F = .55C Cr Mo V - 1500°F - O.Q.
G = .55C Cr Mo V - 1600°F - O.Q.
Note:
Tempering Temperature for E, F & G are by Interpolation.
"P" Values for E, F & G are by Extrapolation
P = (10^3/D) at Optimum Hardness (390 BHN)
Tempering Temperature (°F)
700
800
900
1000
1100
1200
450
470
500
530
550
570
A
B
C
D
E
F
G

FIGURE 16

do, nevertheless, indicate an effect of tempering temperature at temperatures above that at which temper embrittlement would be expected to occur.

V. The Effect of Composition

A. General

The predominant effect of microstructure on the performance of homogeneous armor has been emphasized throughout this review and, therefore, the first requisite of a composition for homogeneous aircraft armor is a sufficient hardenability to obtain the desired microstructure - usually tempered martensite. This hardenability is determined largely by the alloy content. The alloying elements which are most useful for this purpose in the general order of their effectiveness are molybdenum, chromium, manganese and nickel. Armor steels will necessarily contain one or more of these alloying elements and since it has been found that smaller amounts of several elements are more effective than a large amount of a single element, they will usually be used in combination.

Although hardenability is the prime requisite, there are also secondary effects which must be taken into account in choosing a composition. These include a possible specific effect of carbon content, the effect of tempering temperature and the effect of alloys on the tempering behavior, and finally, the effect of the composition on the susceptibility to temper brittleness.

The prerequisites of a composition for homogeneous armor may be summarized as follows:

1. A sufficient hardenability to obtain a microstructure of tempered martensite or lower bainite under the heat treatment conditions to be applied.

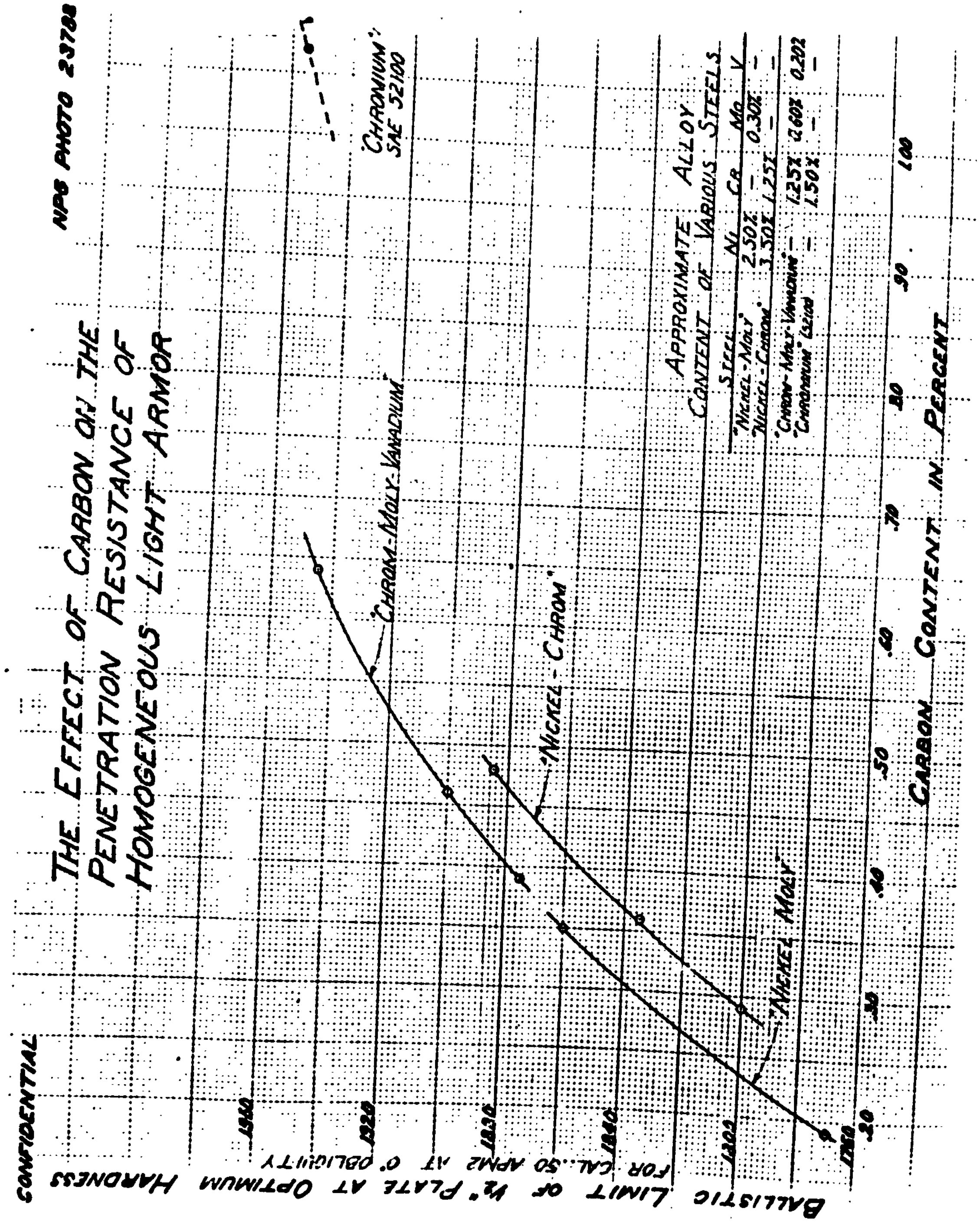
2. An alloy content such that the susceptibility to temper brittleness is minimized. This, in general, implies the lowest alloy content which is consistent with the requisite hardenability, together with the use of sufficient molybdenum (generally at least 0.25%) to minimize the susceptibility. In general, the manganese, phosphorus and chromium contents should be held low unless their effect is offset by the use of a sufficiently high molybdenum content.

3. An alloy content such that the tempering temperature for the optimum hardness for the given ballistic conditions is relatively high (preferably 1100° F. or above). This implies the use of the strong carbide forming elements such as molybdenum or vanadium. This is advantageous in decreasing temper embrittlement as well as in respect to the inherent advantages of the higher tempering temperatures.

4. A relatively high carbon content (.45% and above). There is considerable evidence of an intrinsic advantage of the higher carbon compositions.

B. The Effect of Carbon Content

The factors mentioned above, hardenability, tempering temperature and temper brittleness have all been discussed earlier in this study. Work at the Naval Proving Ground and also at the Naval Research Laboratory has, however, indicated a possible specific effect of carbon content. The Naval Proving Ground results will be cited as illustrative of this effect. These results are presented graphically in Figure 17 as a plot of the ballistic limit of 1/2" plate against .50 caliber projectiles versus the carbon content for steels of four different base compositions. The 52100 steel in this plot was somewhat lacking in hardenability so that it probably does not represent optimum ballistic properties at this carbon content.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NPS PHOTO 23788
THE EFFECT OF CARBON ON THE PENETRATION RESISTANCE OF HOMOGENEOUS LIGHT ARMOR
BALLISTIC LIMIT OF ½" PLATE AT OPTIMUM HARDNESS
FOR CAL .50 APM2 AT 0° OBLIQUITY
"CHROM-MOLY-VANADIUM"
"NICKEL-CHROM"
"NICKEL MOLY"
"CHRONIUM" SAE 52100
APPROXIMATE ALLOY CONTENT OF VARIOUS STEELS
STEEL NI CR MO V
"NICKEL-MOLY" 2.50% - 0.30% -
"NICKEL-CHROM" 3.50% 1.25% - -
"CHROM-MOLY-VANADIUM" - 1.25% 0.60% 0.20%
"CHRONIUM" 52100 - 1.50% - -
.20 .30 .40 .50 .60 .70 .80 .90 1.00
CARBON CONTENT IN PERCENT

FIGURE 17

Although this correlation with carbon content is good, it should be pointed out that the tempering temperature for a given hardness likewise increases with the carbon content and this apparent effect of carbon content may, therefore, be only a reflection of the tempering temperature effect. It is also perhaps significant that the nickel-chrome steels are known to be susceptible to temper brittleness and were tempered in the temper embrittlement temperature range.

C. The Cooperative Homogeneous Aircraft Armor Development Program

A very comprehensive study of the effects of composition was carried on during 1942 and 1943. Heats of seven different basic compositions were prepared by five different manufacturers and rolled to 5/16", 3/8" and 7/8" plates. These plates were distributed to seven different companies for heat treatment. Ballistic testing was carried out in duplicate at Aberdeen and the Naval Proving Grounds. Ballistic tests included .30 caliber A.P. M_2 at 0° and 30° obliquity, .50 caliber A.P. M_2 at 0° and 30° obliquity, 20mm H. E. at 20° and 37mm T.P. M51 at 0°, although not all plates were tested under all conditions.

Code No.	C	Mn	S	P	Si	Ni	Cr	
AA1	.46	.53	.012	.014	.23	--	1.16	.20 V
AA2	.36	.24	.015	.015	.24	3.13	1.17	
AA3	.35	.50	.005	.013	.23	2.33	--	.91 Cu
AA4	.29	1.05	.020	.011	.33	1.05	.14	.27 Cb
AA5	.35	.52	.007	.013	.20	3.50	--	
AA6	.39	.60	.011	.012	.17	--	1.16	
AA7	.48	.27	.017	.013	.28	3.04	1.32	

The results at both proving grounds indicated a decided superiority for analysis AA1. The other compositions fell into approximately the following order of decreasing merit - AA7, AA6, AA3, AA5, AA2 and AA4, although there were individual differences among the various testing conditions and also in some cases between the tests at Aberdeen and those at Dahlgren. The performance of AA4 was consistently the poorest, however, under most of the testing conditions and at both proving grounds. Complete reports of these results are contained in the Naval Proving Ground Report No. 11-43[19] and several Aberdeen Proving Ground Reports.[20] [21] [22]

The results of these tests are in general accord with the factors governing the choice of composition as discussed above. The poor performance of AA4 apparently reflected both a low hardenability and a low carbon content. The other plates all seemed to have sufficient hardenability with the possible exception of some of the 7/8" plates and the performance can in general be correlated with either the carbon content or the tempering temperature for optimum hardness. It was pointed out in the Naval Proving Ground report that the ballistic performance of armor currently being furnished by one manufacturer was superior to the results of composition AA1 on this test. This presumably reflected the higher carbon content (.50% to .60% C) of the then current production armor.

VI. Recommendations for Future Research and Development

A. The Effect of Hardness and Ballistic Variables

1. A comprehensive program is currently being carried out jointly by Aberdeen and Watertown Arsenal. This work should be continued and its results coordinated with the results of studies of the metallurgical factors.

B. Microstructure

1. Further studies aimed at the quantitative evaluation of the effects of upper bainite, ferrite and pearlite on the properties and ballistic performance of tempered martensite. Such work would serve to evaluate the permissible deviations from optimum microstructures and would permit an intelligent evaluation of the minimum hardenability requirements and alloy contents for this service.

2. Similar studies of the effects of undissolved carbides.

C. Heat Treatment

1. In the interest of production and alloy conservation, develop water quenching practices which would permit rapid quenching and still minimize the danger of distortion and quench cracking.

2. Develop and evaluate techniques for rapid tempering in order to minimize temper brittleness.

3. Compare the ballistic performance of martempered and quenched and tempered plates.

D. Homogeneity

1. Studies aimed at a further evaluation of the effects of the types, amounts and distribution of non-metallic inclusions.

2. A further quantitative evaluation of the effects of the degree and the directions of hot working in order to establish limitations which are consistent with an economical commercial practice.

E. Composition

1. Further basic studies of the effects of the alloying elements on full martensite hardenability.

2. Further evaluation of the effect of carbon content. The relative role played by the carbon content itself and the corollary effect of tempering temperatures should be definitely established.

3. Studies of the effects of the alloying elements on the tempering behavior together with studies of the embrittling effect of "secondary hardening".

4. Basic studies of the factors involved in temper brittleness including further evaluation of the effects of alloying elements in this behavior.

5. Development of compositions which can be water quenched without a serious sacrifice of ballistic performance and without serious quench cracking or distortion.

PART 3

FACE HARDENED ARMOR

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FACE HARDENED ARMOR

I. The Purpose of Face Hardened Armor

In contrast to homogeneous armor, where the resistance to penetration by projectiles depends principally on the ability of the armor to absorb the kinetic energy of the projectile, face hardened armor is designed to resist penetration principally by dissipating the projectile's energy through deformation or destruction of the projectile itself. Although high hardness homogeneous light armor has been used at times to attain the same end, the concept of an optimum hardness for homogeneous armor, explained earlier, makes the limited application of such armor readily understood. Face hardened armor therefore may be seen as a combination structure. It has a high face hardness to deform the attacking projectile and a softer more ductile back to support the face material. When face hardened armor cannot cause the projectile to deform, it immediately becomes inferior to optimum quality homogeneous armor since the full energy of the projectile must be absorbed by the armor which because of low ductility in the face portion can absorb little energy by plastic flow.

II. Metallurgical Factors

A. The Hardness Pattern

From the foregoing, it is apparent that three important variables in face hardened armor are the face hardness, the back hardness and consequently the gradient between the face and back. A considerable amount of investigation and experimental work on each of these factors was reported during and immediately after World War II. The reported results for each individual factor will be discussed separately.

1. Face Hardness

Although face hardened light armor had been made by various manufacturers for years, it is evident that the relationship between ballistic performance versus armor piercing projectiles and face hardness may not have been recognized before 1938 or understood too well before 1942. In 1938, the Naval Research Laboratory while commenting on tests reported by Watertown Arsenal[23] and confirmed at the Naval Research Laboratory stated that the ability of 1/4" face hardened plate to break caliber .30 armor piercing cores was noteworthy.[24] Also in 1938, Watertown Arsenal reported on an investigation of thirty-one face hardened plates which had accumulated over the period of years from 1922 to 1938.[25] One of the conclusions reported was that plates which passed specification had an average face hardness of 542 Brinell while failed plates had an average face hardness of 465 Brinell.

The plates studied in the early investigations mentioned above were carburized plates as were all commercially furnished face hardened light armor plates of the time. Investigations of other methods of producing face hardened armor were going on, however, and consequently when the demand for light armor for aircraft increased with the outbreak of World War II at least one company started furnishing nitrided plates. The face hardness of the nitrided armor and carburized armor supplied during the period from 1938 to 1941 was usually high (600 BHN and higher) and the ballistic limits were fairly consistent.

In 1941 and 1942, several firms inexperienced in the manufacture of light armor qualified to produce this material by still another method known as the Pluramelt process. Production difficulties in the form of ballistic failures soon beset two of the companies furnishing aircraft armor to the Navy Department, however, and the Armor and Projectile Laboratory at the Naval Proving Ground, Dahlgren, Va. was requested to investigate the material.[26]

A wide variation in penetration resistance shown by test plates of the new material was noted. In an effort to determine the cause or causes of the wide variation, eighteen 1/2" plates were selected for investigation. Nine were "A" Company plates which had failed to pass the ballistic test, five were "A" Company plates which had passed and four were "B" Company plates which had passed. Upon investigation it was found that whereas the acceptable plates had a minimum face hardness of 555 BHN, none of the plates that failed had a face hardness as high as 555 BHN. Three of the failed plates were retreated at the Laboratory and subjected to further ballistic testing. The hardness and ballistic test results before and after retreatment are shown below.

HARDNESS AND BALLISTIC TEST RESULTS ON THREE PLATES RETREATED AT ARMOR AND PROJECTILE LABORATORY

Plate No.	Condition	Brinell Hardness Face	Brinell Hardness Back	Ballistic Limit vs. .50 Cal. AP at Normal (foot seconds)
3	Original	512	460	1930 failed
3	Retreated	600	430	2330 passed
5	Original	532	387	2020 failed
5	Retreated	600	418	2170 passed
9	Original	532	378	1800 failed
9	Retreated	555	375	2170 passed

Further investigation of plates submitted by the two new light armor manufacturers indicated that the low surface hardness which was blamed for the high percentage of ballistic failures was caused by inadequate heat treatment and/or surface decarburization. The plates retreated by the Laboratory to pass the ballistic test merely showed the benefits to be gained by proper heat treatment. The presence of varying depths (.007" to .030") of surface decarburization was noted and a further investigation to evaluate the effect of decarburization was inaugurated.

In a report[27] dated June 30, 1943, the Naval Proving Ground disclosed their findings concerning the effect of surface decarburization and further confirmed their earlier theories on face hardness. By careful testing and investigation they had determined that a face hardness of 600 BHN is sufficient to fracture the core of the .50 caliber A.P. M_2 projectile. A correlation with the "Knoop" microhardness of the surface layer was equally good. From a large number of plates tested, it was found that if a 1/2" plate has a "Knoop" hardness less than 540 at a depth of .010" the plate will probably fail the .50 caliber test specified in Navy Department, Bureau of Ordnance Specification Number 2775.

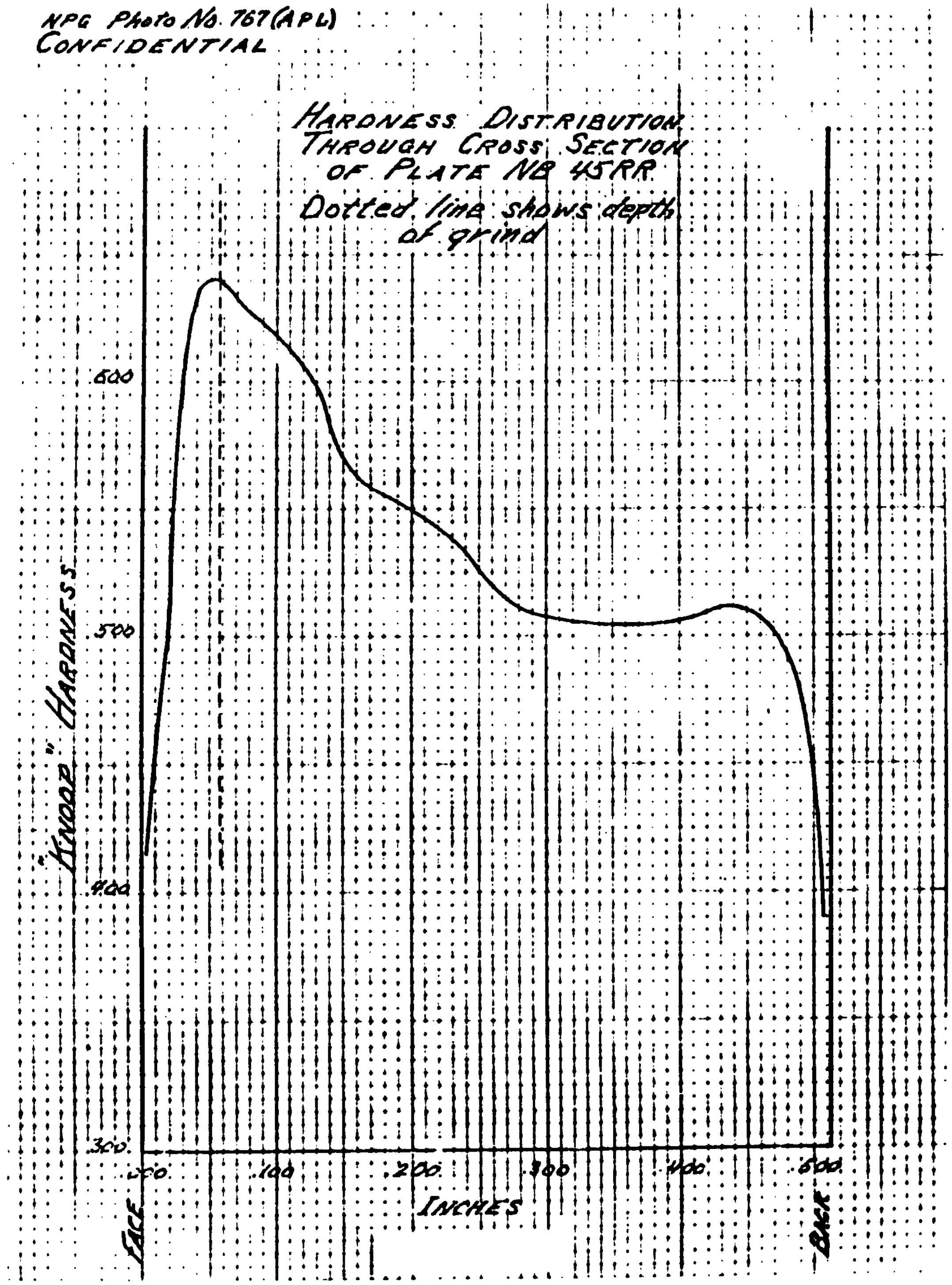
While the foregoing statements regarding minimum Brinell hardness on the face and minimum "Knoop" microhardness at a depth of 0.010" at first appear inconsistent, an understanding of the extent and effect of decarburization clarifies the apparent contradiction. Surface preparation for a Brinell test involves removal of a surface layer to obtain a clean flat surface for the Brinell ball impression. The surface layer removed contains all or at least the worst part of the decarburized portion of the plate cross section. Thus, the minimum 600 BHN face hardness is not found on the face but rather at a slight depth under the face. The material between the actual face and the plane of the Brinell test impression, being decarburized, is softer. The minimum of 540 "Knoop" at a depth of 0.010" therefore defines the allowable depth of decarburization.

During the investigation reported in N.P.G. Report No. 12-43, it was found that the ballistic limit of 1/2" plates vs. .50 caliber A.P. M_2 projectiles could be raised by as much as 800 ft./sec. by grinding off the soft decarburized surface layer. For instance, plate NB45RR had a limit of 1206 ft./sec. as received for acceptance testing, but on grinding the face to a depth of 0.048", the plate limit was raised to 2033 ft./sec. The hardness distribution curve of the plate is shown in Figure 18 where it will be seen that the surface hardness was increased from 400 to over 600 "Knoop" by the removal of the decarburized layer. When the decarburized layer was removed by grinding, the bullet core fractured into many small pieces even on complete penetration and a clean punching was removed from the back of the plate. Typical cores and fragments of .50 caliber bullets fired at ground and unground areas of decarburized plates as shown in Figure 19.

The necessity for a minimum hardness on the face to break hardened steel projectile cores thus has been well established. The earliest suggestion that perhaps there is an optimum face hardness is found in a Naval Proving Ground Memorandum Report.[28] The report concerns an investigation of two 1/2" thick plates which had spalled excessively on ballistic testing. The conclusion of the report are as follows:

> "The cause of face spalling on the subject plates was found to be due to an excessive hardness gradient between the face and the back of the plates. This hardness condition, probably due to an insufficient time at the original draw temperature, was considerably improved by reheat treatment. On a second ballistic test, the resistance to spalling on one plate was found to be markedly improved and spalling was entirely eliminated on the other. It is also to be noted that when the face spalling condition was eliminated, the ballistic limit was increased somewhat."

Figures 20 and 21 show hardness patterns of the two plates investigated before and after reheat treating. It seems significant that the ballistic limit of plate G70-5-38R was increased 50 f.s. by retreating and the peak hardness of the retreated plate was 50 "Knoop" lower than the original



NPG Photo No. 767(APL)
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HARDNESS DISTRIBUTION THROUGH CROSS SECTION OF PLATE NB 45RR
Dotted line shows depth of grind
"KNOOP" HARDNESS
600
500
400
300
.000
.100
.200
.300
.400
.500
INCHES
FACE
BACK

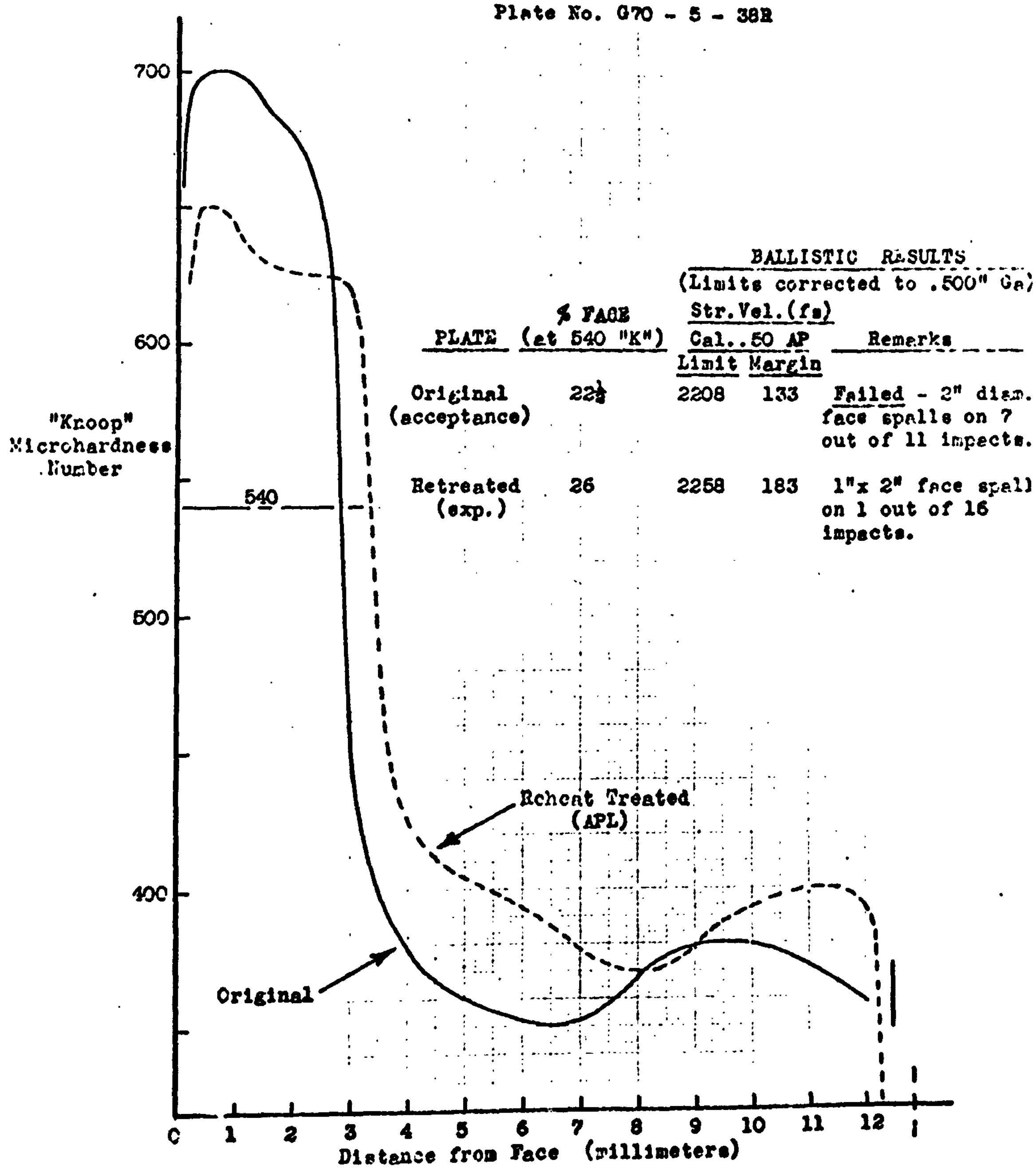
FIGURE 18

NPG PHOTO NO. 769 (APL) - Typical cal. .50 AP M2 cores and fragments recovered after firing at decarburized plates. TOP ROW. Cores that passed through the unground portion of the plate. BOTTOM ROW. Fragments of cores that passed through ground portion of plate together with plate punchings.
May 13, 1943

FIGURE 19

MICROHARDNESS DISTRIBUTION THROUGH CROSS SECTIONS OF 1/2" PLURAMELT LIGHT ARMOR

Plate No. G70 - 5 - 38R



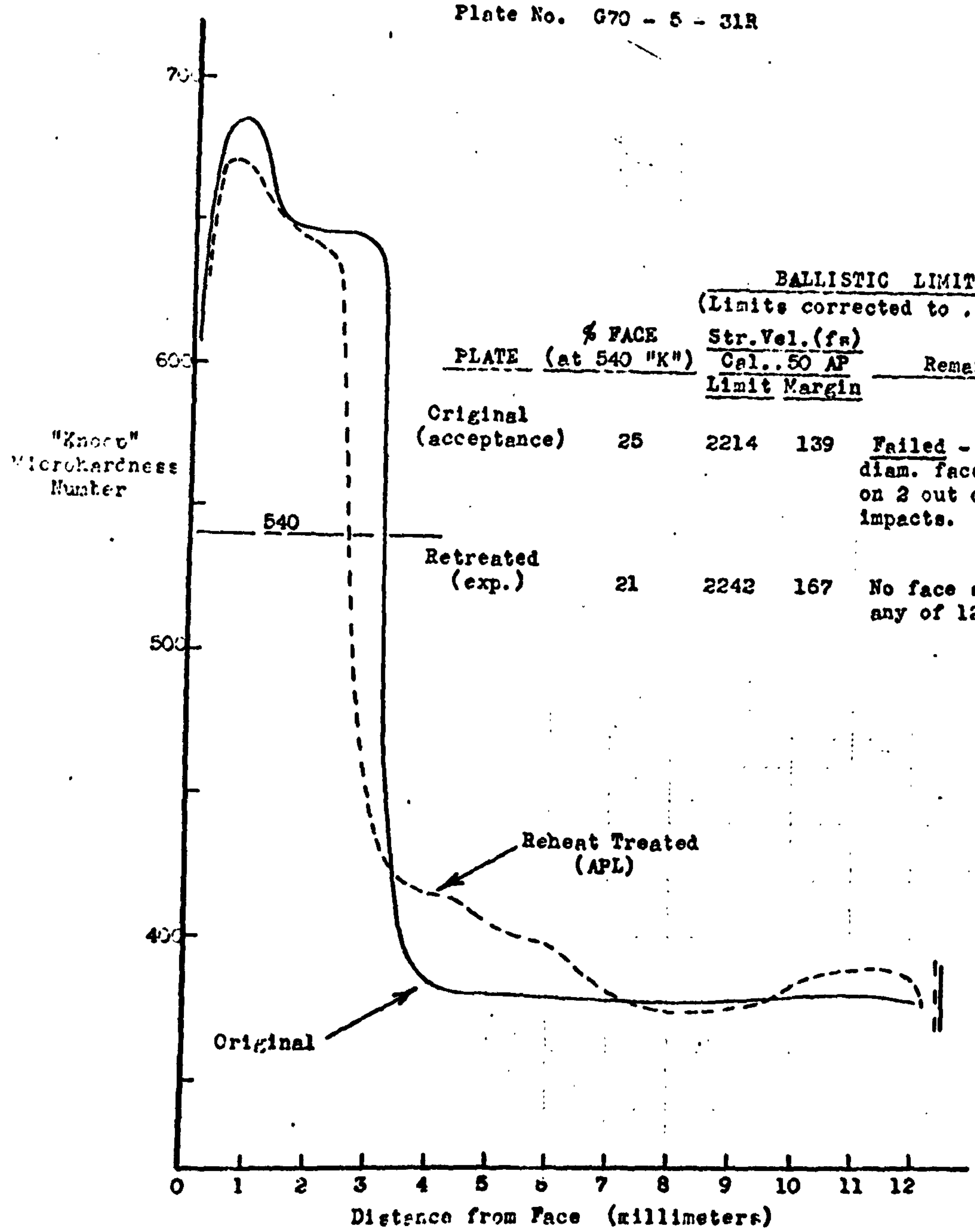
BALLISTIC RESULTS (Limits corrected to .500" Ga)

PLATE	% FACE (at 540 "K")	Str. Vel. (fs) Cal. .50 AP Limit	Margin	Remarks
Original (acceptance)	22½	2208	133	Failed - 2" diam. face spalls on 7 out of 11 impacts.
Retreated (exp.)	26	2258	183	1"x 2" face spall on 1 out of 16 impacts.

FIGURE 20

MICROHARDNESS DISTRIBUTION THROUGH CROSS SECTIONS OF
1/2" PLURAMELT LIGHT ARMOR

Plate No. G70 - 5 - 31R



BALLISTIC LIMITS (Limits corrected to .500" Ga.)

PLATE	% FACE (at 540 "K")	Str.Vel.(fs) Cal..50 AP Limit	Margin	Remarks
Original (acceptance)	25	2214	139	Failed - 1"- 2" diam. face spalls on 2 out of 11 impacts.
Retreated (exp.)	21	2242	167	No face spall on any of 12 impacts.

FIGURE 21

peak hardness. Likewise, plate G70-5-31R had a ballistic limit 28 f.s. higher after lowering the peak hardness. Incidentally, it may also be noted that the depth of face of the reheat treated plate was greater than the original depth in one case and less than the original depth in the other case. The improvement in ballistic performance therefore must be due to the lower face hardness.

A Watertown Arsenal investigator in a report dated March 1, 1945[29] was perhaps more forthright in suggesting that there is an optimum face hardness. In discussing the hardness characteristics of plates under investigation he said:

> "It is felt that the hardness (800 VPN) of the heavier gauge plates is somewhat higher than is desirable in face hardened armor. The hardness of the case should be at the minimum necessary to shatter projectiles.".

Further support of the theory of an optimum face hardness may be found in results of shock tests on face hardened light armor. Tests reported by the Naval Proving Ground[30] have shown that the resistance to shock of 20mm H.E. projectiles at 20° obliquity was impaired by subjecting a number of 3/8" and 1/2" plates to a refrigeration treatment following the regular treatment. Since the refrigeration treatment will be discussed in more detail later it will suffice here to explain that the purpose of such treatment was to raise the face hardness. It is evident from the results of these tests that the optimum face hardness for shock resistance is the same as the optimum face hardness for resistance to penetration of armor piercing projectile cores. The fact that an unusual amount of spalling occurs on excessively hard face plates may possibly give some indication of the mechanism of failure.

Since the hardness and metallurgical characteristics of armor piercing projectiles may tend to change with each successively larger size so may the characteristics of the armor face change with increasing plate thickness. It is therefore suggested that further studies to establish the minimum and optimum face hardness for each of the common thicknesses of aircraft armor be considered.

2. Depth of Face

Although there is evidence to indicate that there had been numerous attempts to determine the effect of depth of face prior to the World War II period, it is apparent that many such attempts were made with the immediate objective of finding a material to meet a certain test condition. A general lack of knowledge of the relative importance of each of the variables in face hardened armor and the lack of a single criterion for determining the depth of face prevented isolation of the effect of depth of face in the early attempts.

At the start of World War II, hardness readings on the face and back of face hardened armor were reported but still there was no mention of depth of face. It was realized by this time, however, that a minimum depth of face was necessary. Various experiments wherein a shallow hardness was imparted to the surface of armor by chromium plating, nitriding or spraying metal had established that point. In general it was believed that the face layer should be fairly deep. This belief likely was based on the fact that heavy face hardened naval armor usually had approximately a 40% chill depth and also the fact that the most successful face hardened light armor had been processed by carburizing the face to a depth of 30% to 40%.

Measurement of the case depth on etched specimens or fracture specimens was a fairly rough estimate at best. Attempts to measure the case depth by analyzing successive thin layers for carbon content and noting the depth at which the ladle carbon content was found also resulted in rough estimates. As abrasive disc cutting machines and small impression hardness testing machines came into more general use, cross section hardness surveys of face hardened light armor were relatively easy to obtain. Arbitrary selection of a hardness level to define depth of face was the next logical step. The Naval Proving Ground Laboratory, in the belief that the effective part of the face on light armor was that with a hardness above 540 "Knoop" (approximately 500 Brinell) established that value as a criterion for measuring the depth of face. They also contended that this depth could be accurately determined because of the steep hardness gradient at 540 Knoop. Metallurgical investigation reports published by the Watertown Arsenal Laboratory in 1944 and 1945 referred to 550 VPN as the criterion for determining the depth of face. This value is consistent with the value adopted by the Naval Proving Ground.

It is believed that the most important work in isolating the effect of depth of face was done during 1943 and the years following. Armor produced by the "Pluramelt" process was used for the investigation. In this process a 2" layer of high carbon alloy steel is deposited by an electric arc on a base metal slab of a low carbon steel of similar alloy content. The composite slab is then rolled to the required plate gauge. A wide variation in the ratio of face to back was obtained for the experiments by varying the thickness of the slab on which the 2" layer of high carbon steel was deposited. Untreated plates of 3/8", 1/2", 5/8" and 7/8" were procured for the experiments. Following heat treating by the Armor and Projectile Laboratory at the Naval Proving Ground the plates were subjected to various ballistic tests.

Results of the ballistic tests and metallurgical investigations of representative samples of the Pluramelt plates used in the depth of face experiments were reported in detail by the Naval Proving Ground.[31] [32]

Figures 22, 23 and 24 from the later proving ground report illustrate the effect of depth of face under various test conditions. Both the standard "Navy Limits" and "Statistical Limits" were computed and plotted for the heavier plates. The "Statistical Limit" method of computation is based on the overall average performance of a given plate considering all projectile impacts made against the plate, whereas, the standard "Navy Limit" used as a basis for acceptance tests of production light armor plate is dependent upon the single lowest complete projectile penetration obtained on the plate.

It will be noted in Figure 22 that the curve for 3/8" material is rather well defined. On the other hand there is a lack of certainty in the shape of the curve and in the location of the maximum in the curve for 1/2" material. In fact, the proving ground reported that there was some evidence that the curve is not a continuous function. The plates with a large percent of face failed with large buttons being thrown from the back of the plate instead of failing with clean punchings as is usual for plates of lower percent face. The change in the mechanism of plate failure probably causes an abrupt break in limit velocity.

Although comparison of Figure 23 with Figure 24 shows a higher optimum range for the 7/8" plates (32% to 42%) than for the 5/8" plates (below 30%), it should be noted that different type projectiles were used for the two different gauges, that is, 20mm A. P. M95 for 5/8" and 20mm A. P. M75 for the 7/8". Hence the relationship observed on the 3/8", 1/2" and 5/8" plates vs. caliber .50 A. P. M2 projectiles, that as the gauge is increased, the optimum percent face increases, cannot be strictly interpreted from Figures 23 and 24 because of the differences in weight of the projectiles used. The change from the lighter 20mm A. P. M95 projectiles to the heavier M75 projectiles was found necessary in order to penetrate completely the heavier 7/8" plates.

NPG Photo No. 2784(APL)
23 July 1945.

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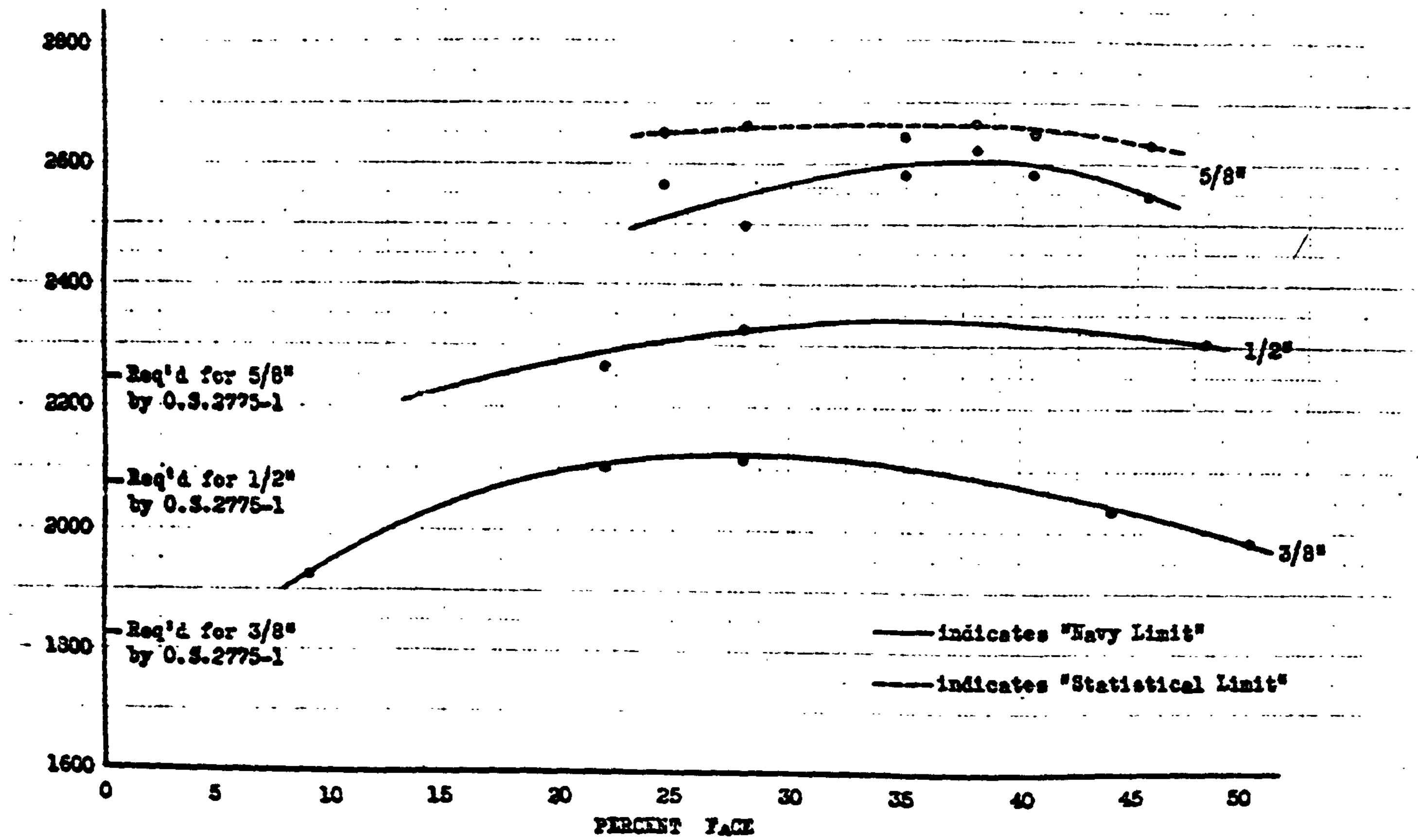
VARIATION IN LIMIT VELOCITY WITH PERCENT FACE
FOR 3/8", 1/2", and 5/8" [illegible] PLATES
(vs. Cal. .50 AP M2 Projectiles at 0° Obliquity)



NPG Photo No. 2785(APL).
23 July 1945.

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VARIATION IN LIMIT VELOCITY WITH PERCENT FACE
FOR 5/8" [illegible] PLATES
(vs. 20mm AP M95 Projectiles at 0° Obliquity)

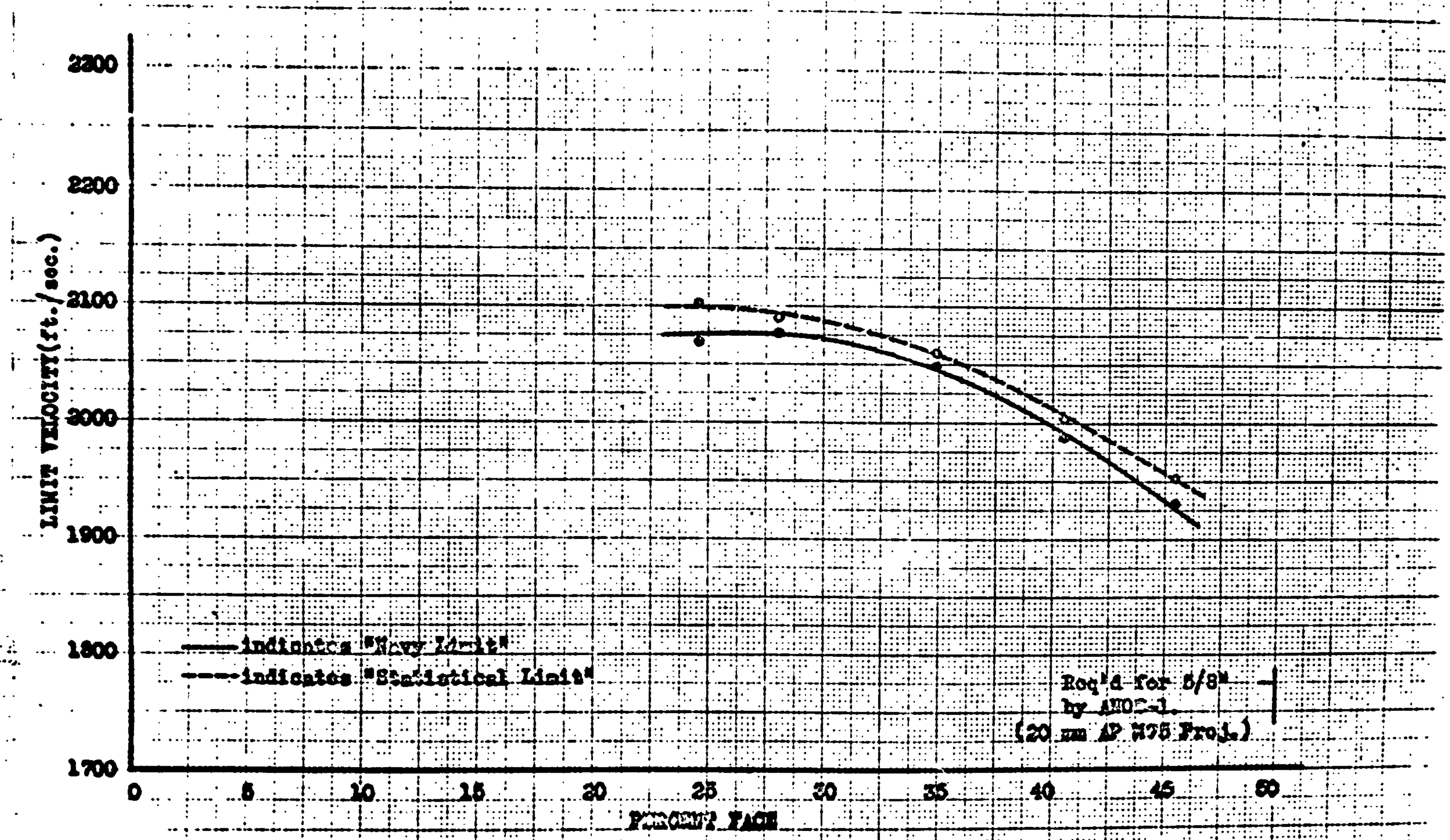

FIGURE 23

NPG Photo No. 2786(APL)
23 July 1945.

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VARIATION IN LIMIT VELOCITY WITH PERCENT FACE
FOR 7/8" PLURAMELT PLATES
(vs. 20mm AP M-3 Projectiles at 0° Obliquity)

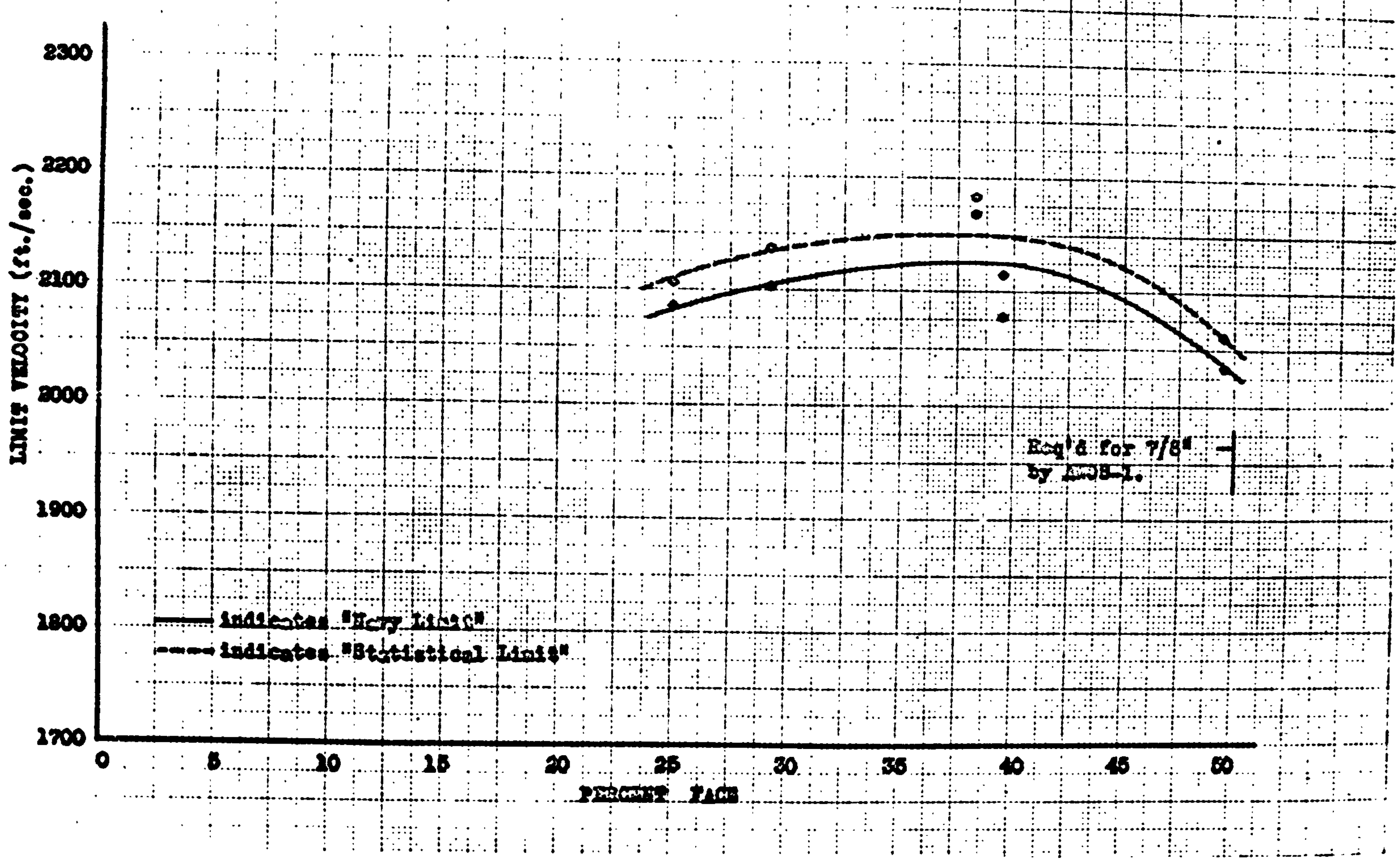


FIGURE 24

It is interesting to note that shock tests with 20mm high explosive projectiles at 20° obliquity were also conducted on the 3/8" and 1/2" material in the depth of face experiments. The results of the shock tests were not quite as clear cut as the results of the penetration tests. All 1/2" plates excepting one passed the shock test specified under Ordnance Standard 2775-1. (It was believed that the one exception failed because of an irregularity). On 3/8" plates, however, failures by the terms of the specification occurred on all plates with 50% face. Failure by shock of a burst of .50 caliber armor piercing projectiles at high velocity occurred on practically all 3/8" plates with 30% or more face.

An interesting and important comparison of the effect of depth of face on carburized armor vs. Pluramelt armor is shown in Figure 25. The data for various depths of carburized face (as determined by 540 Knoop criterion) was found in Naval Proving Ground memoranda concerning investigations of carburized plates.[33] [34] While the data overlaps in only a narrow range, the fact that the slopes of the curves appear to be practically the same indicates that a good correlation exists.

The fact that a good correlation between depth of face and limit velocity exists would seem to be very significant and worthy of extensive development. The effect of changes in e/d ratio on the relationship has not been mentioned although it is apparent that there may also be found a good correlation with that factor. The change in the mechanism of failure noted by the Naval Proving Ground seems very significant and should be considered in planning future investigations of the effect of depth of face.

3. Back Hardness

Lack of understanding of the effects of face hardness and depth of face until recent years naturally resulted in a lack of rigid control of these variables. Without rigid control of face hardness and depth of face, the effects

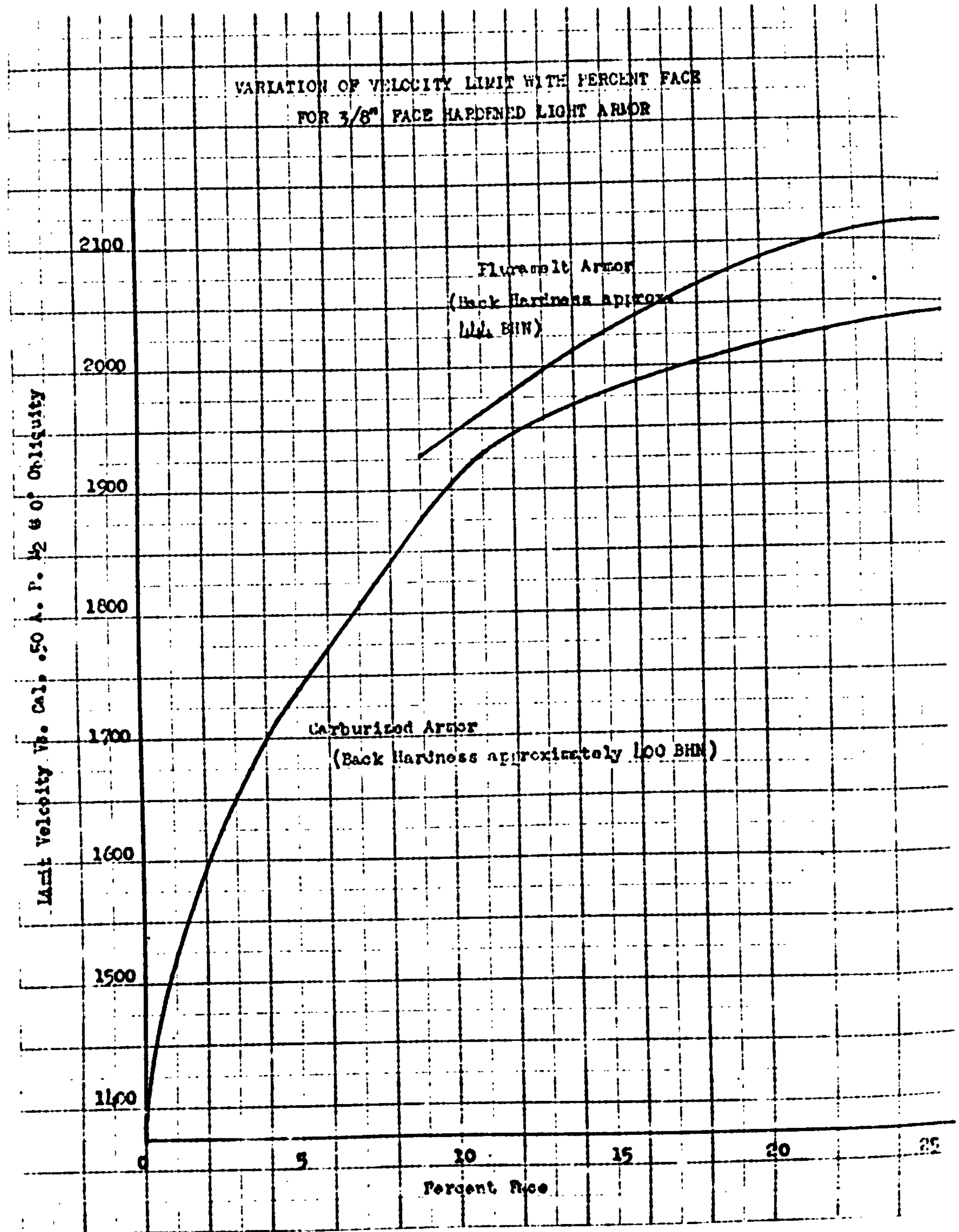

VARIATION OF VELOCITY LIMIT WITH PERCENT FACE
FOR 3/8" FACE HARDENED LIGHT ARMOR
Fluramelt Armor
(Back Hardness approx.
444 BHN)
Carburized Armor
(Back Hardness approximately 400 BHN)
2100
2000
1900
1800
1700
1600
1500
1400
Limit Velocity Vs. Cal. .50 A. P. M2 @ 0° Obliquity
0
5
10
15
20
25
Percent Face

FIGURE 25

of back hardness could not be completely isolated. It has been noted by the Naval Proving Ground, however, that the effect of back hardness on penetration resistance may be so strong that it may be observed even without control of the other variables. In a statistical study of a group of acceptance test plates submitted for ballistic test in 1942, the following correlation was found.

Back Hardness, BHN	Percent Failures
400 - 600	8%
360 - 400	14%
300 - 360	50%

The above correlation apparently points toward a high back hardness. On the other hand, numberous reports of investigations of brittle failures have attributed the failures to too high back hardness. In discussing the results of the depth of face experiments on 3/8" plates, the Naval Proving Ground commented:(31)

> "Plate G8B with 28% face failed the 20mm shock test. No cause could be seen for the failure of this plate except that the back hardness of the 3/8" plates may be too high for this gauge. The back hardness of all 3/8" plates was above 450 Knoop and even above 500 in one case. It would seem that for optimum ballistic properties of 3/8" face hardened armor against caliber .50 A.P. M2 bullets or 20mm H.E., the depth of face and the back hardness should both be less than for 1/2" plates against the same projectiles."

The suggestion that the back hardness should change with changes in the depth of face and e/d ratio is an important one. As far as is known, the interrelation of these functions has not been explored. While the most recent recommendation of the Naval Proving Ground is to furnish a back hardness of 400 to 450 BHN, it is conceivable that an improvement in average performance may result from a more restricted working range wholly within or overlapping either end of the recommended range, depending on the combination of test conditions to be met.

B. Microstructure, Heat Treatment, Composition and Homogeneity

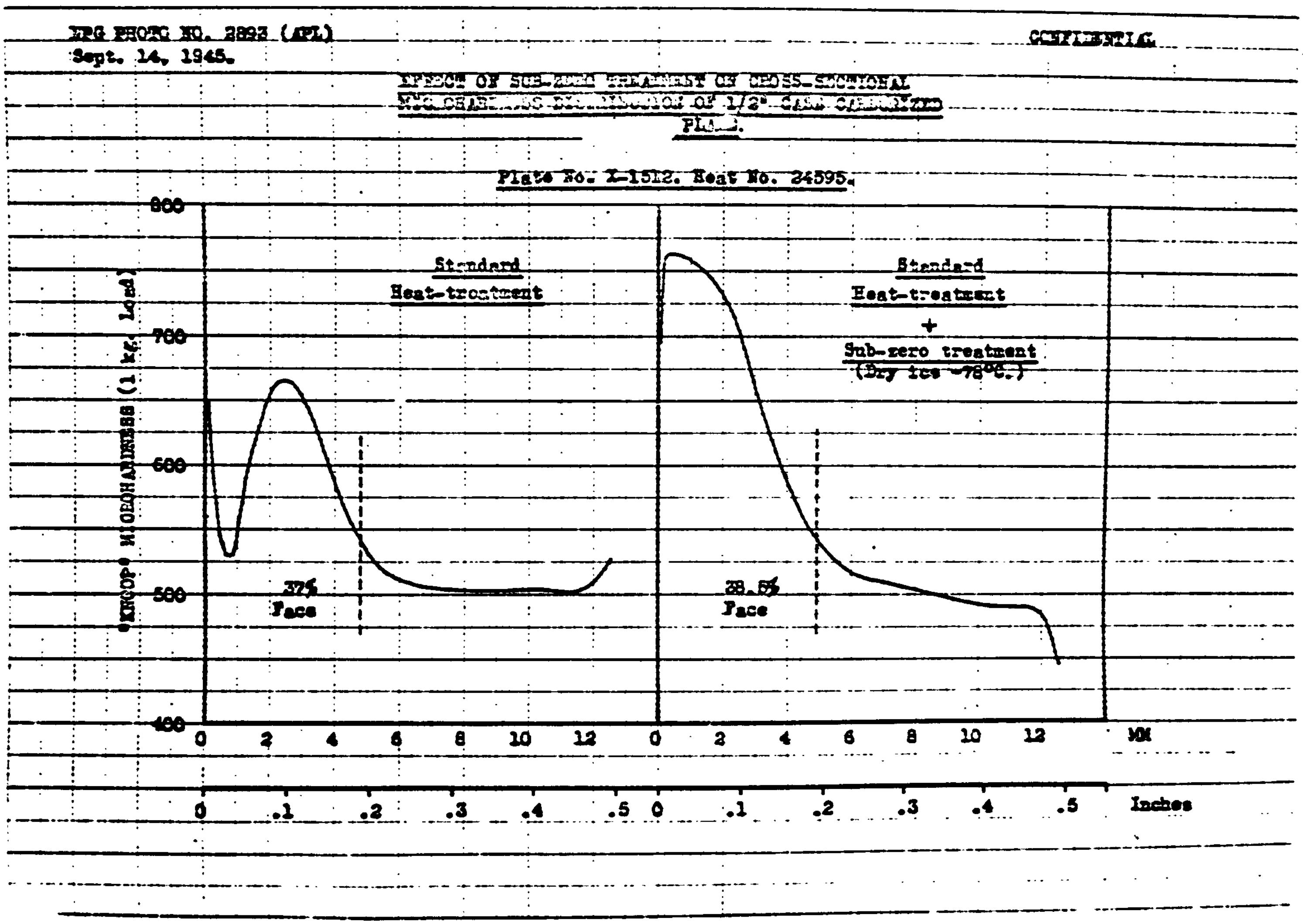
The general comments regarding the metallurgical factors (1) microstructure, (2) heat treatment, (3) composition and (4) homogeneity presented earlier in this study (see pages 30 and 31) apply with equal importance to face hardened light armor. As these factors were shown to be interrelated in their effects on homogeneous armor, so too are they interrelated in their effects on face hardened armor. However, because face hardened armor is more complex in its nature, due to the hardness pattern, it is essential that more rigid control of the metallurgical variables be maintained.

The high hardness required makes it necessary to have a homogeneous tempered martensitic structure in the face portion of face hardened armor. It has been found that the presence of retained austenite in the face (which was not unusual on production armor) lowers the face hardness and therefore adversely affects the limit velocity of the plate.

Experimental refrigeration of plates at dry ice temperatures to transform retained austenite to martensite has increased limit velocities by as much as 200 ft./sec. The hardness patterns of a 1/2" plate before and after refrigeration is shown in Figure 26. This illustration, taken from a Naval Proving Ground letter report(34) shows that the maximum hardness was increased 100 Knoop by refrigerating at -78° C. for 12 hours following the standard oil quenching treatment.

Investigation at Dahlgren, Va. and at the Watertown Arsenal Laboratory have disclosed that face spalling may be attributed to undissolved carbides(35) and in some cases to the presence of carbides in the grain boundaries.(48)

When the 20mm H. E. shock test was introduced in armor specifications many plate failures occurred. Upon investigation the presence of proeutectoid ferrite in the back was noted (Figure 27). Here again was evidence that a mixed



EPG PHOTO NO. 2893 (APL)
Sept. 14, 1945.
CONFIDENTIAL
Plate No. X-1512. Heat No. 24595.
Standard
Heat-treatment
Standard
Heat-treatment
+
Sub-zero treatment
(Dry Ice -78°C.)
37%
Face
28.5%
Face
KNOOP MICROHARDNESS (1 kg. Load)
800
700
600
500
400
0
2
4
6
8
10
12
MM
0
.1
.2
.3
.4
.5
Inches

FIGURE 26

NPG PHOTO NO. 1901 (APL) - CONFIDENTIAL - 15 September 1944

Photomicrograph of the Back of 1/2" Face Hardened Light Armor Plate

Structure: Proeutectoid ferrite in a matrix of low carbon tempered martensite. (M-69)

Magnification: 250X Etch: 4% Picral.

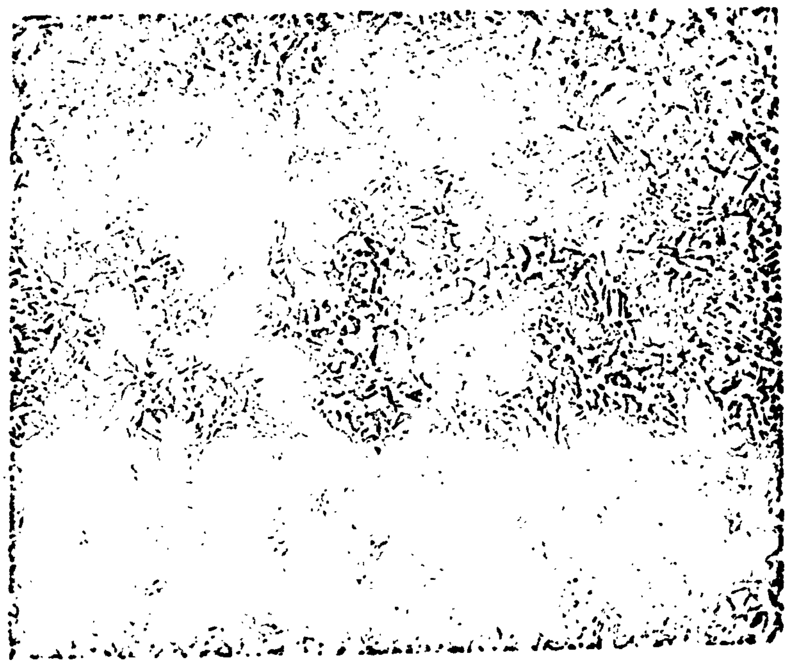


FIGURE 27

microstructure does not have the efficiency of tempered martensite. Watertown Arsenal noted the presence of ferrite in the back of low alloy face hardened armor compositions and attributed inferior shock resistance of the armor to the poor microstructure. The superiority of a homogeneous tempered martensite microstructure in the back of face hardened armor therefore has been well established.

The heat treating practices employed by various manufacturers of face hardened light armor did not vary greatly from firm to firm. In general, heat treatment consisted of a single quenching treatment followed by a low temperature drawback. Individual variations depended on the method employed to alter the composition and hardness of the face portion.

Carburizing, of course, had been the only method used in production of face hardened light armor for many years. A serious disadvantage of pack carburizing was the resultant high carbon content of the face which made it difficult to prevent the retention of austenite on heat treating. Attempts to minimize retention of austenite by quenching from a lower temperature usually resulted in undissolved carbides in the face and proeutectoid ferrite in the back. Two possible methods of overcoming the handicap of the high carbon content were developed during the World War II period. The first method was to diffuse the carbon by high temperature long time homogenizing treatments; such as holding for 24 hours in a salt bath at 1600° F. and air cooling before the standard quenching and tempering treatment. The alternate method was to transform retained austenite by refrigeration.

Plates made by the Pluramelt process did not have the extremely high carbon content on the face but on the other hand were generally found to be decarburized at the face. The lower carbon content of the decarburized surface layer made it necessary to resort to water quenching to insure obtaining the required face hardness in many cases.

Notwithstanding the exceptions noted above, the hardening treatment on most face hardened armor was as follows:

1550/1575° F. for 1 to 1-1/2 hours

Oil quenched

300° F. for 1 hour

Water quenched cold

Since the predominant effect of microstructure had been emphasized throughout the references mentioned above it was to be expected that a review of the compositions utilized for face hardened armor would show that they had been designed to obtain the desired microstructure - tempered martensite. In general this was a fact. The nickel-molybdenum composition used for carburized light armor before the water continued in favor. Conservation of strategic materials during the war period resulted in a slight lowering of the nickel content but numerous references attest to the fact that the altered composition had sufficient hardenability to produce a martensitic structure in sections as heavy as 1/2". Investigations at Dahlgren showed that the nickel content should be raised to 4% to 5% for plates of 5/8" and 7/8" thickness. Occasionally, small percentages of chromium were added to this composition.

The makers of Pluramelt after unsuccessful experiments with a high chromium face composition also adopted a 3-1/2 to 4% nickel - 0.40% molybdenum analysis. References to the use of a chromium-molybdenum-vanadium composition for carburized armor were noted but little data on microstructure and properties of this analysis were found.

Considerable work on the development of low alloy NE steels for face hardened armor was performed by or under the direction of Watertown Arsenal Laboratory personnel during the war years. Some degree of success was obtained in making 3/8" face hardened armor of the NE composition but in the overall program the NE steels suffered in comparison with plates of a 4% Ni-0.15/0.20 Cr - 0.25/0.30 Mo composition.[29]

There is little factual evidence to show the effect of inhomogeneities in face hardned armor. Nevertheless, the high hardness of face hardened armor would be expected to accentuate any inferiority in steel soundness. One reference to the effect of non-metallic inclusions was furnished by the Naval Proving Ground.[35] There it was stated that large non metallic inclusions are frequently found in the face portion of Pluramelt armor and they tend to cause face spalls. An example of the type of inclusions found in the face of Pluramelt armor is shown in Figure 28.

III. The Manufacture of Face Hardened Armor

In view of the foregoing discussions on face hardened light armor, such armor may be defined as steel armor plate which has been so processed either by special heat treating procedures or by chemical alteration of the face layer that it has acquired a hardened face layer extending to a controlled depth with the balance of the section being considerably softer and more ductile. Actually all of the face hardened aircraft armor produced commercially has been made by some variation of the second method mentioned in this definition. Difficulties encountered in producing face hardened armor by the first method are readily recognized. Obviously, prior treatment to establish the required back properties would have to be followed by a surface treatment to obtain the required face hardness. To prevent alteration of the back properties, already set by prior treatment, surface heating must be fast and closely controlled. Even then, there is produced a zone between the hardened face layer and the unaffected back which will have a mixed microstructure and therefore offer little resistance to penetration by projectiles. Notwithstanding these difficulties, considerable

NPG PHOTO NO. 1191 (APL).
Photomicrograph of large sub-surface stringer in 1/2" Pluramelt light armor (40%) Face. Left - as annealed. Right - as hardened showing soft pearlite band in tempered martensite.
Magnification: 250X Etch: 4% Picral.
25 October 1943

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FIGURE 28

effort to develop a flame hardening technique was expended during the World War II period. In general the experiments on light armor were unsuccessful.

The second method of producing a hard face layer, i. e., chemical alteration of the face portion, has had several variations. For discussion purposes, these variations may be grouped in three types: (1) Carburized Armor, (2) Nitrided Armor and (3) Composite Armor.

Carburized armor is the oldest type of face hardened aircraft armor known. In carburized armor the high face hardness required is obtained by raising the carbon content of the face layer. For years prior to World War II pack carburizing methods were used. During the war period, however, liquid bath carburizing and gas carburizing methods were also employed with success. Officers at the Naval Proving Ground reported that in their opinion, the latest developments in gas carburizing should eliminate the major difficulty encountered in carburized armor. The difficulty referred to is the high carbon content which usually resulted in retained austenite at the face. Ballistic tests on carburized armor produced during the war period are equal to the highest on record.

To date, Pluramelt armor is the most important type of composite armor produced commercially. In the Pluramelt process a high carbon (approx. 0.60%) steel layer is melted onto a low carbon (approx. 0.20%) slab of similar alloy content by an electric arc located at the interface and the composite slab is then rolled down to the required plate gauge. For the experiments on depth of face, the maker of Pluramelt armor held the thickness of the face layer constant and varied the thickness of the base steel slab to control the percentage of face in the rolled plate. It was apparent that difficulties in manufacturing increased with increased percent of face. In fact, company representatives stated that face cracking and separation at the interface was encountered on slabs having a nominal face of 40% to 50%. As a result, no 1/2" plates having a nominal face of 50% were delivered for the experiments.

Other disadvantages of Pluramelt have been mentioned previously. Decarburization at the surface results from heating for rolling and subsequent high temperature treatments. As long as decarburization is held to a minimum, ballistic efficiency of the heat treated plate is not impaired. The large non-metallic inclusions trapped in the face material during melting must also be held to minimum.

Manufacture of face hardened light armor by depositing hard facing compounds, such as stellite, on a suitable back plate has been attempted at different times without success. In 1940 and 1941, Watertown Arsenal investigated the merits of Colmonoy No. 1 and Dyronhard No. 65, two high alloy hard facing compounds, for local surface hardening or quick repair of armor plate.[36] These attempts were also unsuccessful.

Worthy of mention at this point, is the fact that during recent years a major steel company has produced experimental heavy composite armor plates made by a double pouring method. To date, as far as is known, face hardened light armor has not been made by this method. It is believed that light armor to compare with carburized or Pluramelt armor could be produced by the double pouring method.

The last method for producing composite armor to be discussed, for lack of a better name, shall be called "Roll Welded" armor. In this method slabs of suitable thickness and composition are carefully cleaned on adjoining surfaces, then heated and rolled as a "sandwich". The pressure exerted by the rolling mill and the high temperature of the "sandwiched" slabs during rolling results in a weld at the interface. Attempts to process armor plate by such a method are not new; the idea has long been intriguing. Past attempts have failed because of a separation at the interface.

A new variation of the roll welded method has been patented by B. Liebowitz of New York. Liebowitz interrupts the rolling of the "sandwich" slab to give the steel a high temperature homogenizing treatment. By this treatment he claims to get a carbon diffusion across the welded bond into the lower carbon material. Rolling is then completed and the resulting plates are heat treated in the usual manner. Liebowitz's experimental plates were investigated by Watertown Arsenal Laboratory in 1941. Apparently because the results were not outstanding the plates were considered as another failed attempt and the idea was dropped. Looking back, it may be significant that Liebowitz's first tests were as good as they were.

It seems to be worth while to continue experiments on roll welded armor. Dahlgren has such material from two different sources on hand now. Although preliminary results discussed with personnel at Dahlgren indicate that one of the materials on hand is no better than past attempts, the second material seems to give promise. The advantages of control and uniformity of product over the range of thicknesses used for aircraft armor made possible by development of a roll welded practice would be important.

PART 4

SPECIFICATIONS FOR STEEL AIRCRAFT ARMOR AND EFFECTS OF IMPROVEMENT IN QUALITY

I. Specifications for Steel Aircraft Armor

The correlation of metallurgical characteristics with ballistic properties has been a continuous, ever improving process. As various factors upon which ballistic performance depends were learned, specification requirements were raised and better armor plate was demanded of industry. The successive improvements and specification requirement increases developed quite rapdily particularly during the early war years, as a direct result of the vast quantity of armor produced. Many plates were tested ballistically and a large amount of technical data gradually accumulated. As this data became available, first one variable and then another could be isolated. Finally interdependence of variables was recognized.

The improvements resulting from increased knowledge were accomplished despite the great deal of confusion that existed prior to the war. It was mentioned in the introductory section of this study that specifications for aircraft armor did not exist at the time United States was drawn into World War II. Therefore, both the Army and the Navy first procured armor for aircraft to existing specifications for light armor plate and "bullet proof" steel.(37) (38) While both the Army and the Navy specifications permitted the use of face hardened or homogeneous material, the ballistic requirements were so high that manufacturers were forced to furnish face hardened armor. Since the manufacture of face hardened armor was a highly specialized and somewhat difficult process, few concerns were attracted to the field.

For those manufacturers attracted to the armor plate business, it must have been disconcerting to learn that although the specifications permitted the use of homogeneous armor successful ballistic test results could not be achieved with such material. Likely, it was also confusing to a new manufacturer to find that the Army and Navy each had their own criteria for acceptance. For example, Specification AXS-54K, Rev. 4 specified that a 3/8" thick plate had to resist "Complete Penetration" by a caliber .30 A.P. M2 projectile at 2250 f.s. (at normal incidence). "Complete penetration" was considered to have been obtained when any portion of the bullet or projectile protruded through the plate; or, when by impact, a hole had been made in the rear face of the plate of any size whatsoever, sufficient to admit the passage of light or produce spalls, buttons, cracks or slivers in the rear of the plate. Specification O.S. 595 required a 3/8" thick plate to resist "complete penetration" by the caliber .30 A.P. M2 projectile at 2315 f.s. (at normal incidence). Only in this case, complete penetration was considered to have been obtained when the bullet core passed completely through and fell behind the plate.

Despite the confusion surrounding the specifications, the steel aircraft armor suppliers joined in the defense effort and produced satisfactory face hardened armor. However, as war neared and tonnage requirements increased, it became apparent that the aircraft building program would be delayed unless the country's aircraft armor capacity was rapidly expanded. It was realized at this time that for certain installations within a plane, homogeneous armor which could be manufactured with less difficulty than face hardened armor would suffice or even be advantageous. In fact, the British started ordering homogeneous armor at about the same time in order to prevent damage resulting from fragmentation of bullet cores. Thus, it came about that specifications for homogeneous armor were written and the nation's aircraft armor capacity was expanded to meet the increasing demands of the aircraft industry.

The first specifications for homogeneous steel aircraft armor still differed on definition of a complete penetration. Army specification AXS 605[39] required a 3/8" thick plate to resist complete penetration of caliber .30 AP M2 projectiles at 1550 f.s. (at normal incidence) whereas the Navy Specification O.S. 2380[40] required 3/8" material to resist penetration of the same projectile at 1755 f.s. In the first case the pinhole of light criterion ruled while in the latter case the bullet had to pass through the plate to be called a complete penetration.

The specification requirements for homogeneous steel aircraft armor were increased rapidly during 1941 and 1942 as production of armor increased. Navy Department Specification O.S. 2498[41] dated just a year after the above mentioned O.S. 2380 shows that the minimum velocity at which a complete penetration (bullet through plate criterion) was permitted was 2060 f.s. for the same test conditions mentioned in the foregoing examples. The increase over the requirements of O.S. 2380 for the sample test condition was 17%. In addition to the increased resistance to penetration specified, improved resistance to shock was also required. Whereas O.S. 2380 limited the size of exit holes on complete penetrations and specified that no cracking should occur on impact, the later specification, O.S. 2498, provided for an additional shock test by 20mm H.E. projectiles and specified the type and amount of damage resulting from the test that would be permitted. In fact, it gradually became apparent after the effect of hardness was recognized that in many cases the shock test was the governing test. Evidence of this is found in a Naval Proving Ground memorandum report[42] which shows that a major supplier of homogeneous steel aircraft armor experienced 11% failures on the 20mm shock test on 61 groups of 3/16" and 1/4" armor furnished in 1943.

No further increases in "Resistance to Penetration" requirements for homogeneous steel aircraft armor were made after 1942. Late in 1942, however, the Army abandoned the pinpoint of light criterion (on aircraft armor testing) and collaborated with the Navy in preparing Specification A.N.O.S. 1[43]. In 1945 joint Army-Navy Specification JAN-A-256[44] superceded A.N.O.S. 1. Worthy of mention at this point is the fact that while both the Army and Navy finally adopted the Navy "projectile through plate" criterion, controversy concerning the merits of one criterion versus the other continued. Late in 1943, Watertown Arsenal published a report which pointed out the disadvantages of both criteria and proposed consideration of a "Lethal Limit" criterion.[45] Although this proposal apparently did not find favor when Specification JAN-A-256 was prepared, the report as a whole is recommended for its realistic approach to the problem of specifying ballistic requirements.

Ballistic test requirements of face hardened steel aircraft armor also increased during the war years. Typical resistance to penetration requirements are shown in the following table.

Period:	1940-43	1943	1944
Specification:	O.S.595[38]	O.S. 2775[46]	ANOS No. 2[47]
Test Condition:	Velocity in feet per second		
1/4" plate vs. cal. .30 A.P. @ 0°	1915	1975	1995
3/8" plate vs. cal. .50 A.P. @ 0°	1765	1825	1855
1/2" plate vs. cal. .50 A.P. @ 0°	2065	2075	2075

As in the specifications for homogeneous steel aircraft armor, shock test requirements for face hardened armor were also increased during the period being discussed.

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II. Possibilities of Further Improvements

There are two considerations in determining whether or not further improvements in steel aircraft armor are possible. First, is there evidence to show that armor of maximum efficiency is now being produced, and secondly, is it possible to increase the average efficiency of armor?

Insofar as homogeneous steel aircraft armor is concerned, the possibilities of increasing the maximum efficiency heretofore attained appear to be very limited. In the part of this study dealing with homogeneous armor, the authors attempted to show that the ballistic performance at an optimum hardness is primarily determined by the toughness of the material. Optimum toughness at optimum hardness, in turn, is primarily dependent upon microstructure and the optimum microstructure is tempered martensite.

Data now available permits determination of the optimum hardness for each of the common ballistic test conditions. Since the basic importance of this variable was first recognized, the Army has been carrying on an extensive program to determine the "Effect of Hardness" on any given set of ballistic conditions. Upon completion of this program, the armor metallurgist will have full knowledge of the fundamental requirement, optimum hardness. While there is no indication that the Army does not intend to continue its program, the authors' recommendation A. 1. (page 30) that the work should be continued is for the express purpose of emphasizing the importance of the work.

Since the optimum microstructure is known to be tempered martensite, recommendations B. 1 and 2. (page 31) would not be expected to result in further increases in maximum efficiency. However, such studies should bring about ultimately a general improvement in average quality.

Recommendations C. 1, 2 and 3 and D. 1 and 2 are also aimed at improving average quality. It will be noted that these recommendations are concerned primarily with production problems.

It would appear that the recommendations concerning further studies on composition offer the most fertile field for future development. Recommendations E. 1 and 2 (page 31) stand out among all as being those most likely to result in increasing the maximum efficiency of homogeneous armor. Reference is made to Figure 17 to support this suggestion. Recommendations E. 3, 4 and 5 (page 32) would serve to further increase knowledge and understanding of factors expected to be encountered in carrying out recommendations E. 1 and 2.

In contrast to the situation just discussed wherein there appeared but little hope for increasing the maximum efficiency of homogeneous aircraft armor, the study of face hardened armor seems to indicate that further improvement of that material is possible. This situation exists despite the fact that homogeneous aircraft armor was developed to its present high level within the war period, whereas face hardened armor had been in use long before the war. The reason for the situation is apparent in the study of face hardened armor. Not until high precision metallurgical instruments and techniques were employed in the investigation of a large number of ballistically tested plates was it possible to isolate effects of the most important variables in face hardened armor. Although these variables were being isolated at the same time the fundamental requirements of homogeneous armor were being learned, the complexity of the hardness pattern alone in face hardened armor obscured the relative importance of each variable within the pattern. As a result the interdependence of different variables had not been fully learned at the war's end.

It will be recalled that several recommendations for development work were made in the course of discussion on face hardened armor. All of the recommendations, however, pertained to the hardness pattern. The recommendations on page 39 regarding face hardness, on page 42 regarding depth of face, and on page 43 regarding back hardness are related and of equal importance. Implementation of a research program based on these recommendations could ultimately result in an empirical formula for determining the optimum hardness pattern for any given test condition. The other suggestions made, page 49, pertain to possible new methods for attaining the optimum hardness pattern once the pattern itself is known.

In considering what improvement is possible or expected as a result of the suggested research program, the following summary of past and predicted results for a single test condition is pertinent. In the case of Navy 1/2" face hardened armor vs caliber .50 A. P. projectiles at normal incidence, the minimum limit velocity required by Specification O. S. 595 was 2050 f.s. During 1941 and 1942 the average limit velocity of more than 1900 plates tested was about 2130 f.s. More than 1000 of the plates tested were of the Pluramelt type and the average depth of face of 1/2" Pluramelt armor was 20%. On Figure 22, note that the optimum depth of face for 1/2" armor is apparently over 30%. The depth of face experiments and various other investigations of face hardened armor conducted and reported in 1944 and 1945 led the Naval Proving Ground to recommend increasing the minimum limit requirement for 1/2" armor to 2267 f.s. since the results of the various experiments had shown that limits consistently above this figure were possible. Although this specification requirement increase has not been made to date, the recommendation is a matter of record.[30] It is apparent, therefore, that an increase of about 150 f.s. in limit velocity over that prevailing in 1942 is immediately possible. The fact that the optimum hardness pattern as a whole has yet to be determined leads to the belief that still further improvement is also possible.

The foregoing conclusions of the authors are in agreement with opinions of armor metallurgists at Watertown Arsenal and the Naval Proving Ground. While illustrations supporting the major points of the conclusions were taken from reports published by the latter agency, Watertown Arsenal representatives expressed the same opinions, in general, during a discussion at the Arsenal Laboratory in the course of this study.

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